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(54) **COMBUSTION CHAMBER CONSTRUCTIONS FOR OPPOSED-PISTON ENGINES**

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(51) **Int. Cl.**

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F02B 23/06	(2006.01)
F02B 75/28	(2006.01)
F01B 7/02	(2006.01)

(52) **U.S. Cl.**

CPC ***F02B 75/282*** (2013.01); ***F02B 23/0651*** (2013.01); ***F02B 23/0678*** (2013.01); *F02B 2275/48* (2013.01); ***F02B 23/0633*** (2013.01); ***F02B 23/0621*** (2013.01); ***F01B 7/02*** (2013.01); *Y02T 10/125* (2013.01); ***F02B 23/0624*** (2013.01)

USPC .... **123/301**; 123/51 B; 123/299

(58) **Field of Classification Search**

CPC F02B 23/104; F02B 23/0618; F02B 23/0621; F02B 23/0624; F02B 23/0633; F02B 23/0639; F02B 23/0675; F02B 23/0678; F02B 23/069; F02B 23/0693; F02B 75/28; F02B 75/282; F02B 7/02; F02B 25/08; F02F 3/26; F02F 3/28

USPC .... 123/51 R, 51 B, 51 BA, 51 BD, 53.3, 123/53.6, 55.2, 55.5, 55.7, 73 C, 193.6, 251, 123/261, 262, 279, 285, 289, 290, 299–301, 123/303, 306, 307, 661, 667, 46 R, 276

See application file for complete search history.

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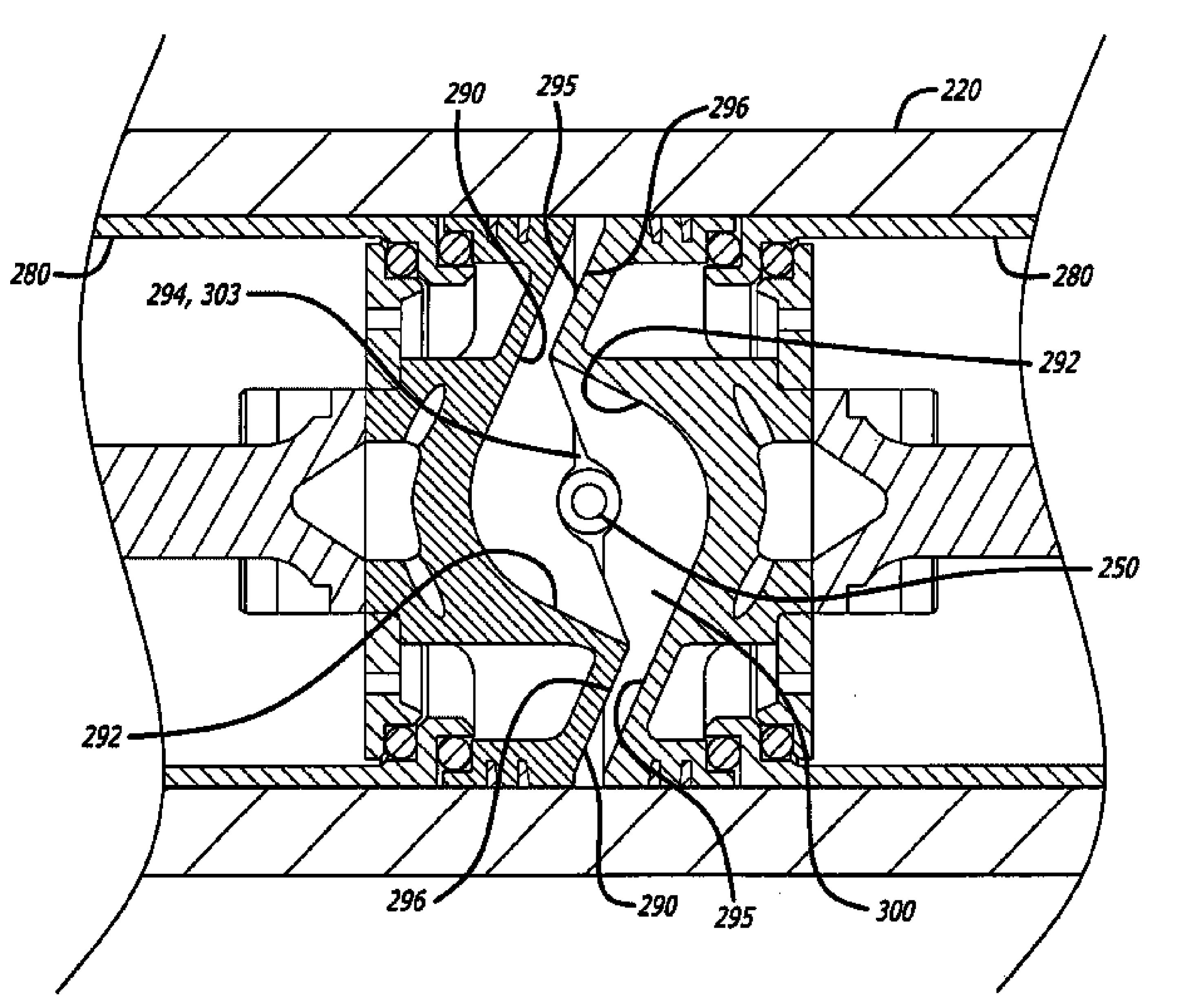
(57) **ABSTRACT**

A combustion chamber for an opposed-piston engine includes a squish zone defined between circumferential peripheral areas of opposing end surfaces of the pistons, a cavity defined by one or more bowls in the end surfaces, and at least one injection port that extends radially through the squish zone into the cavity. The cavity has a cross-sectional shape that imposes a tumbling motion on air flowing from the squish zone into the cavity.

16 Claims, 13 Drawing Sheets



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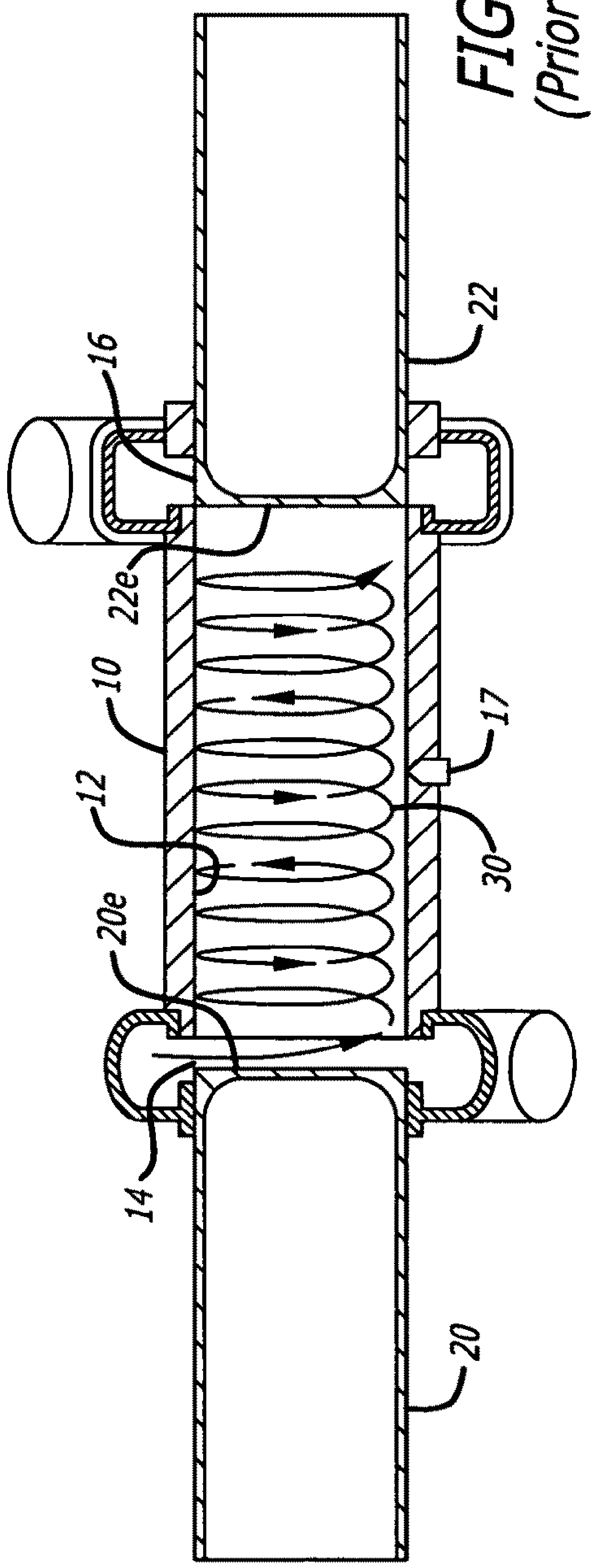


FIG. 1
(Prior Art)

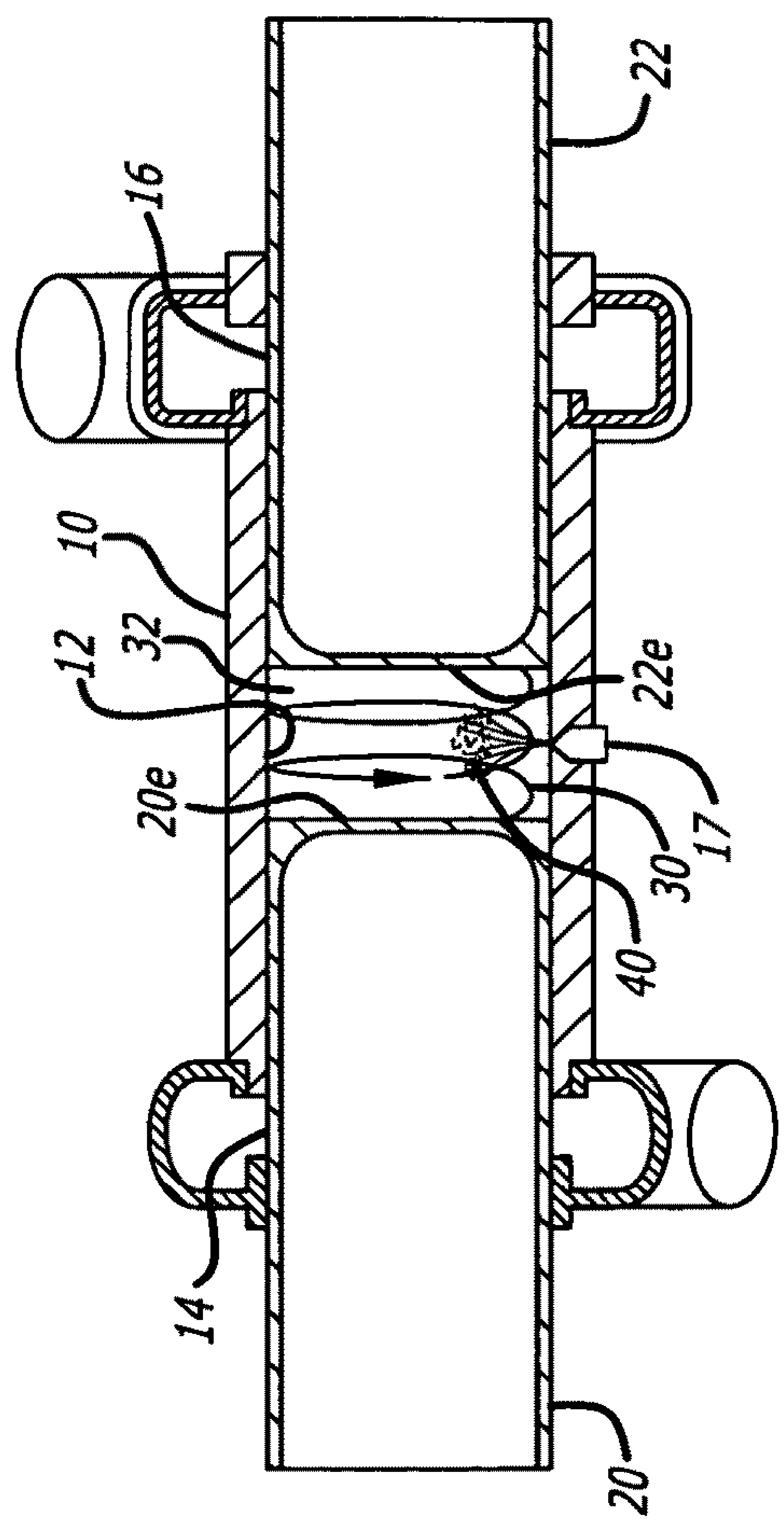


FIG. 2
(Prior Art)

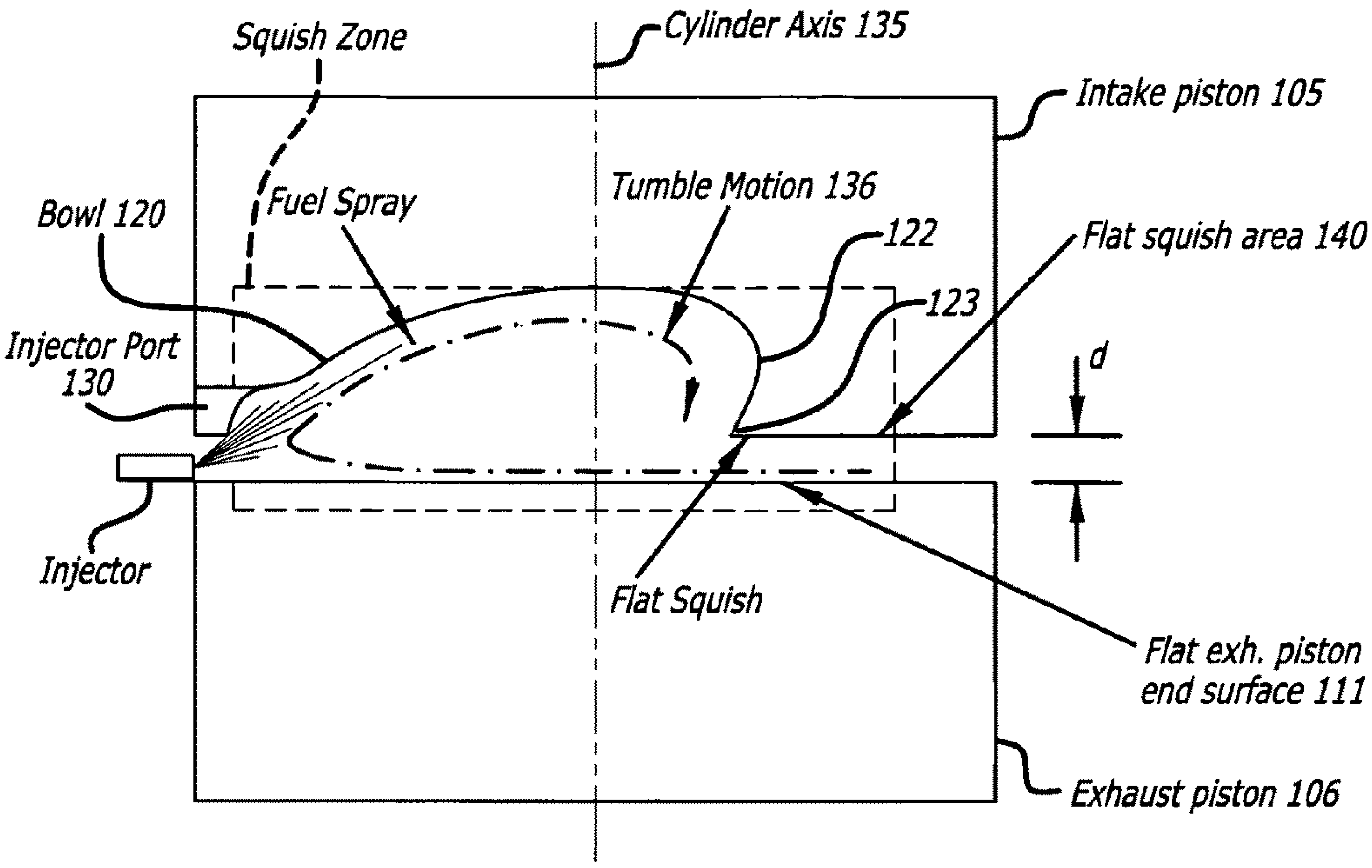
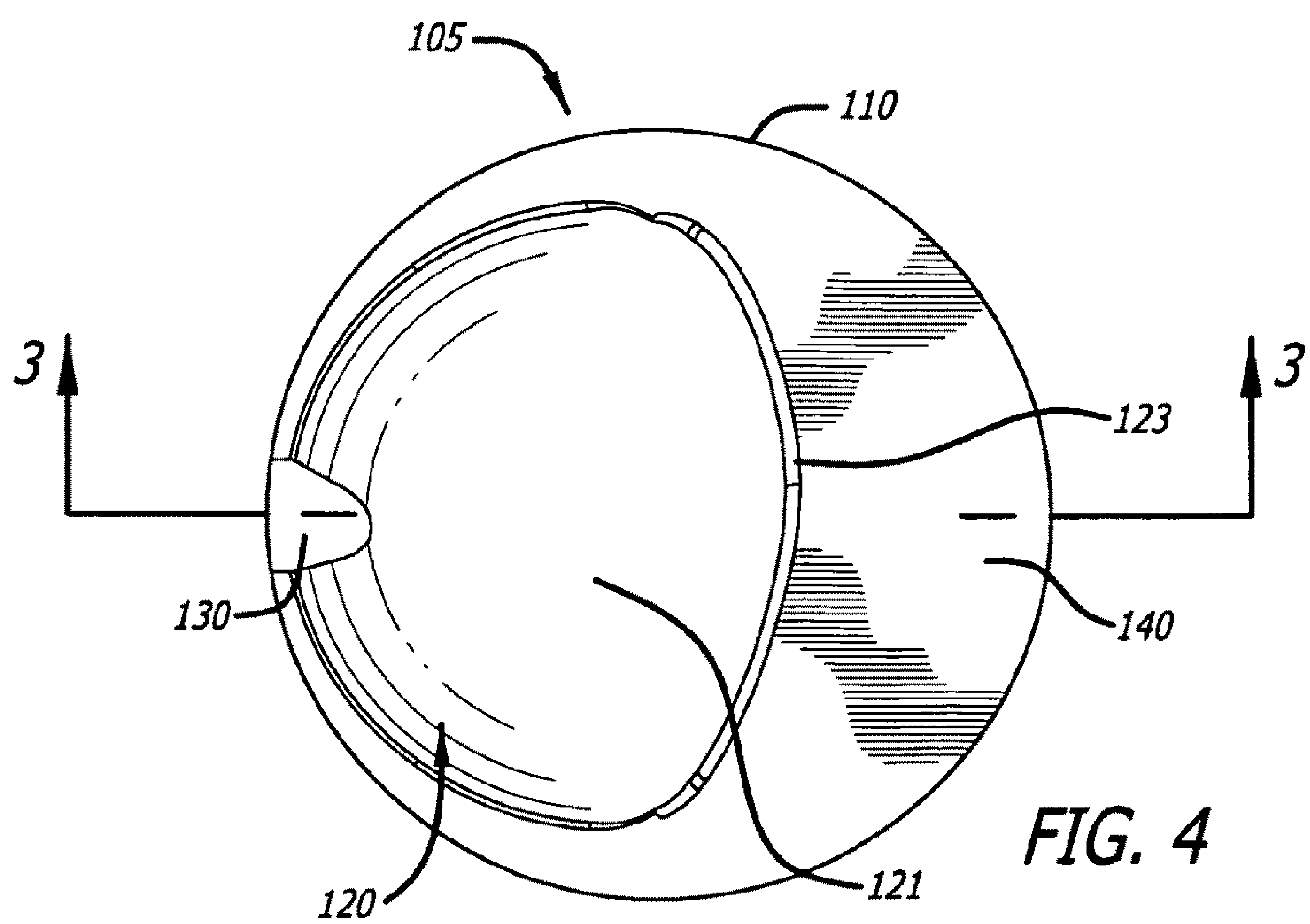

Squish Zone
Cylinder Axis 135
Intake piston 105
Bowl 120
Fuel Spray
Tumble Motion 136
122
Flat squish area 140
123
d
Injector Port 130
Injector
Flat Squish
Flat exh. piston end surface 111
Exhaust piston 106

FIG. 3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121

FIG. 4

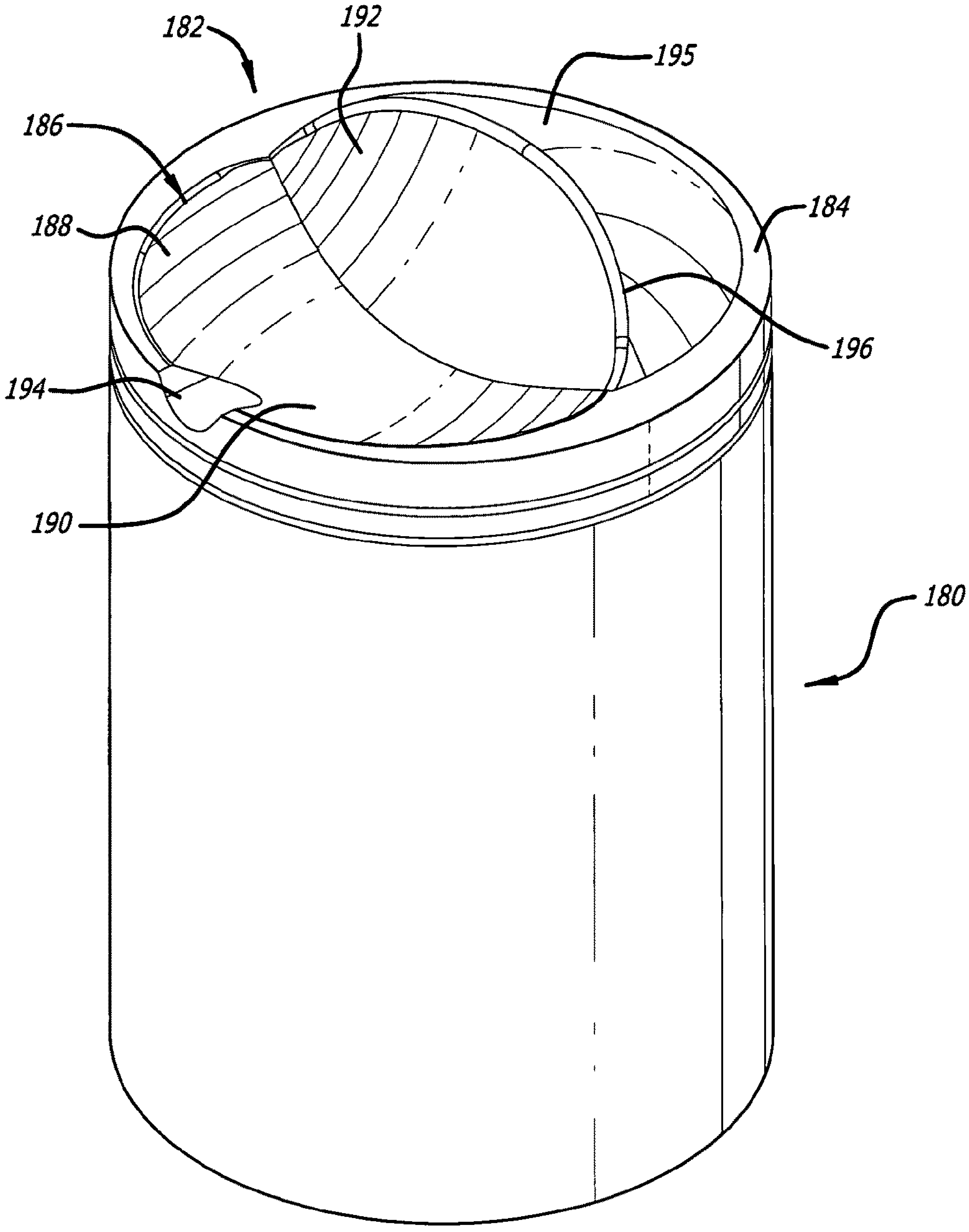


FIG. 5

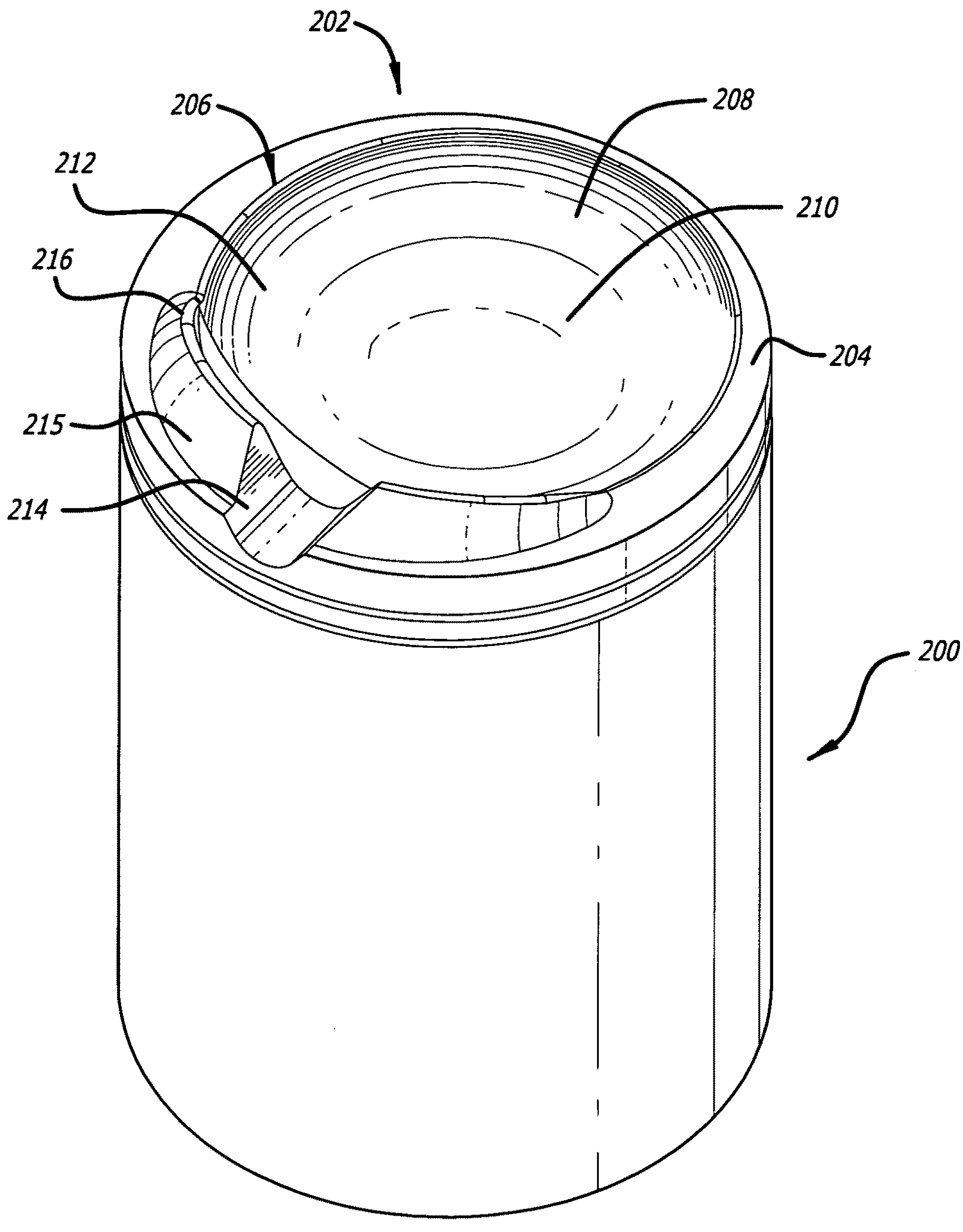


FIG. 6

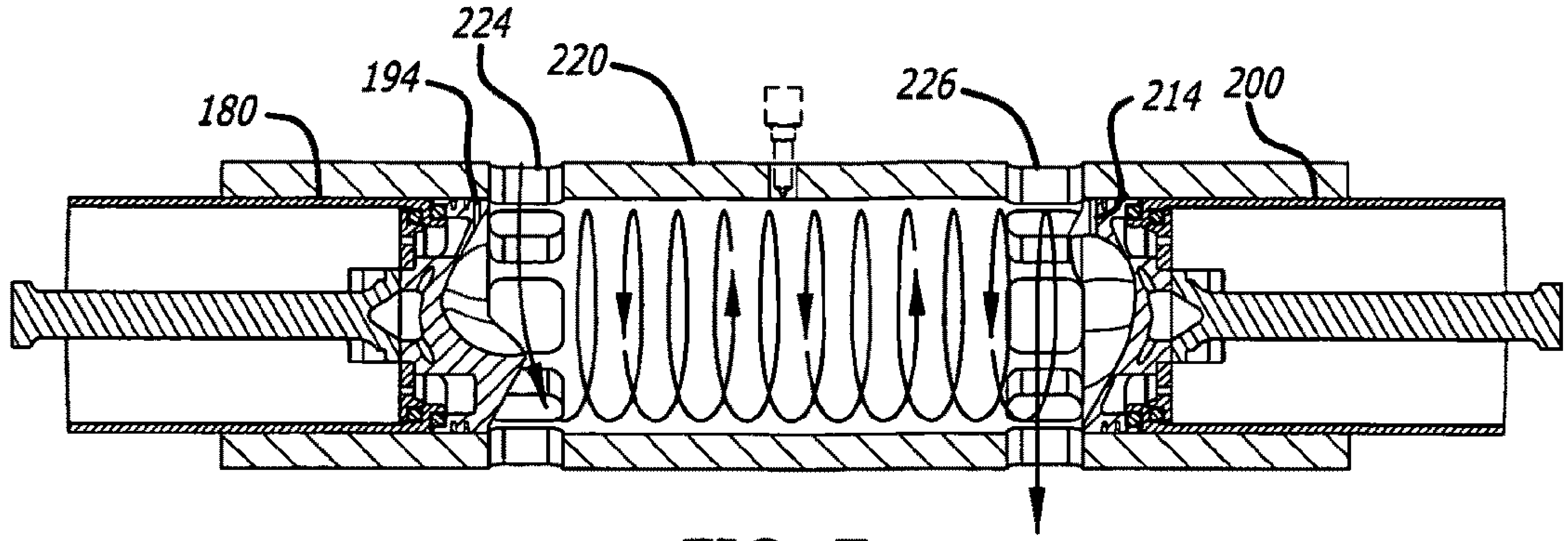


FIG. 7

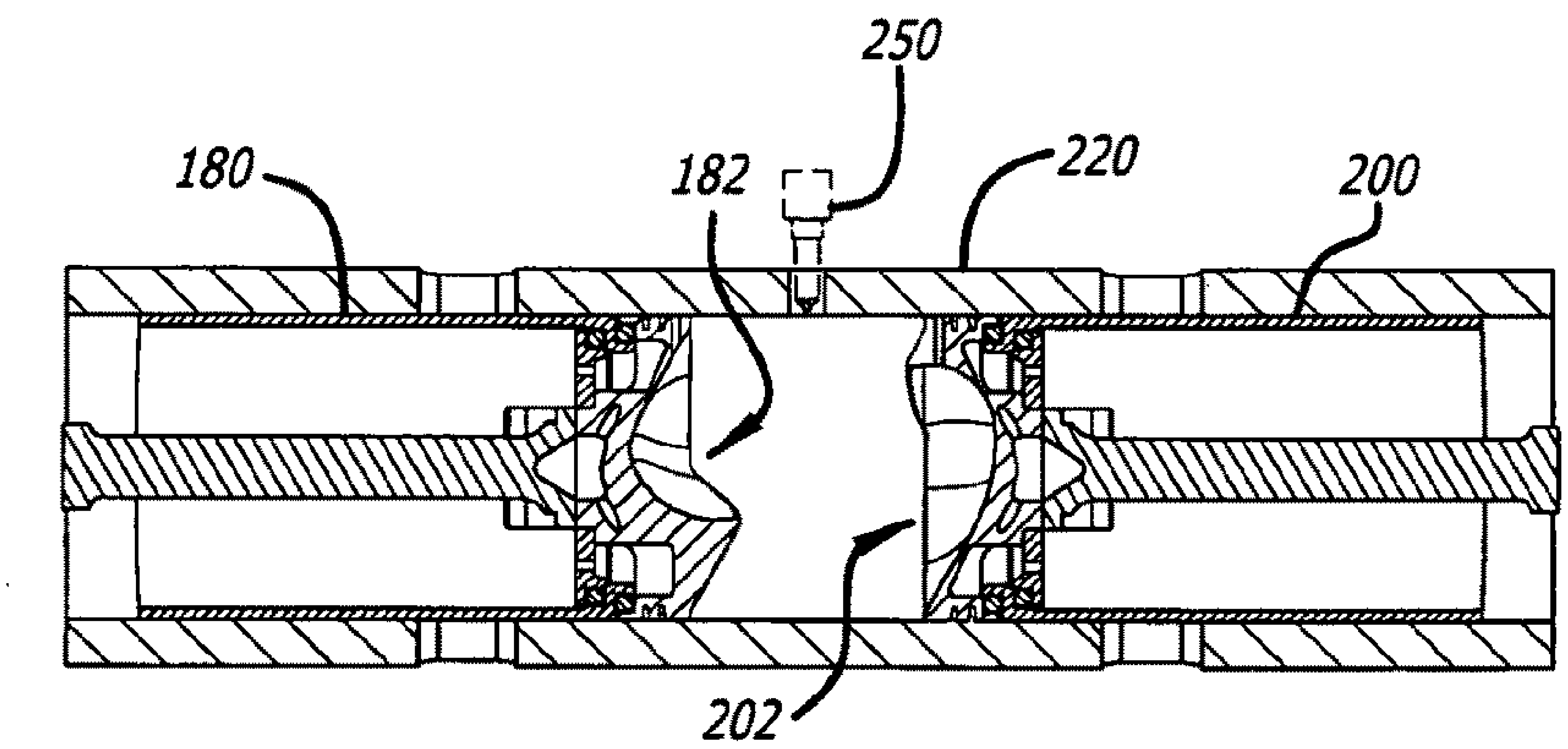


FIG. 8

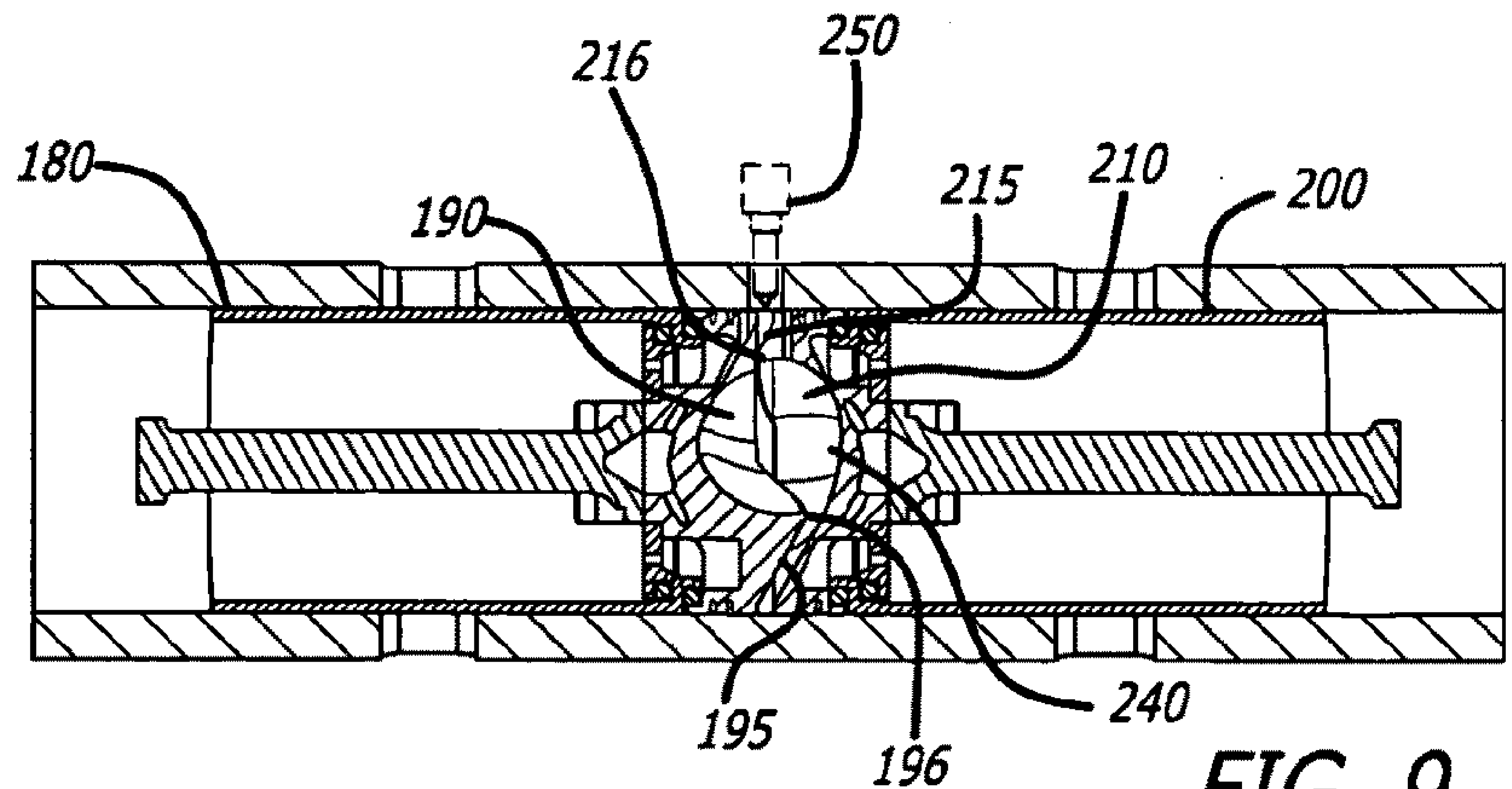


FIG. 9

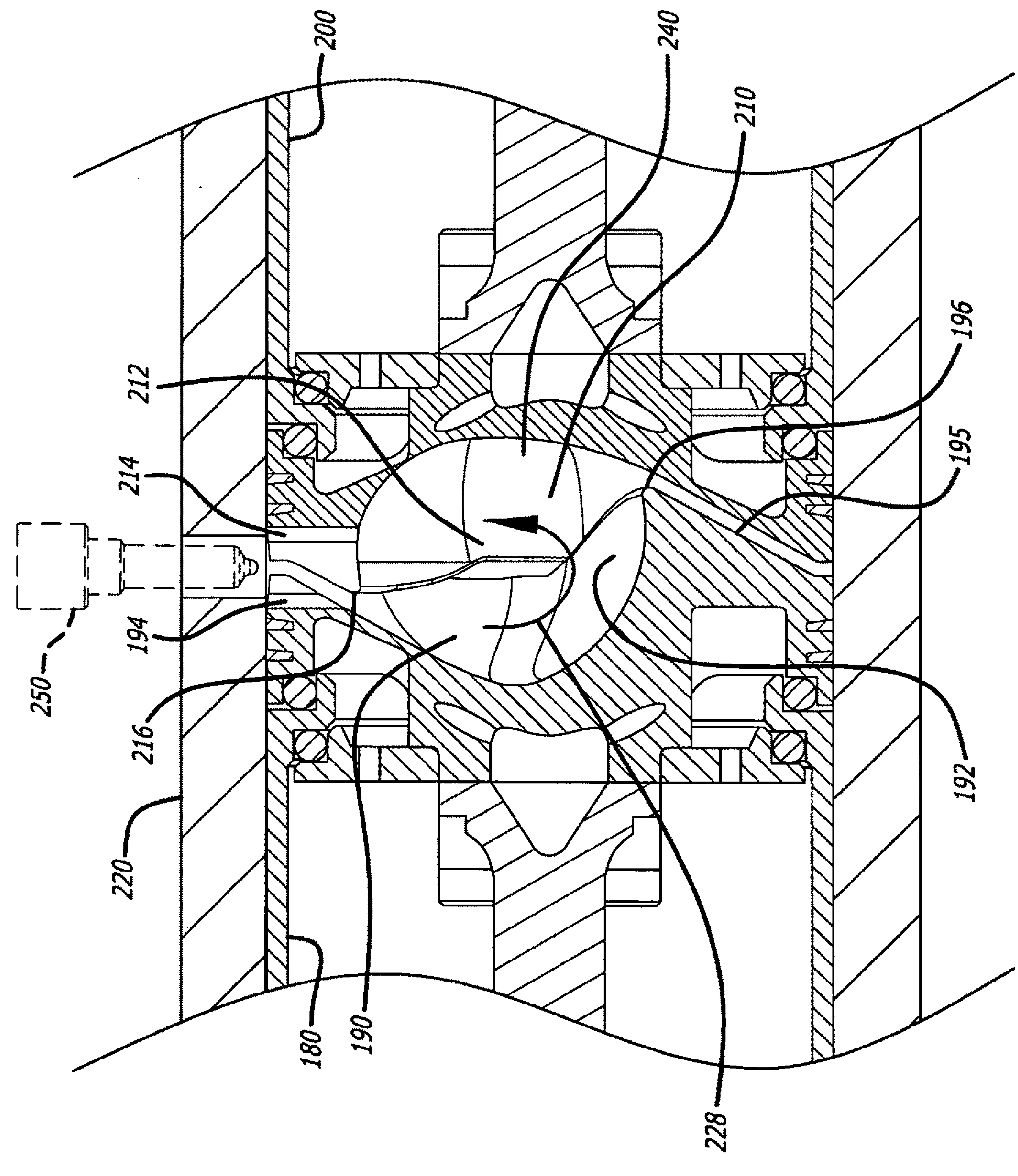


FIG. 9A

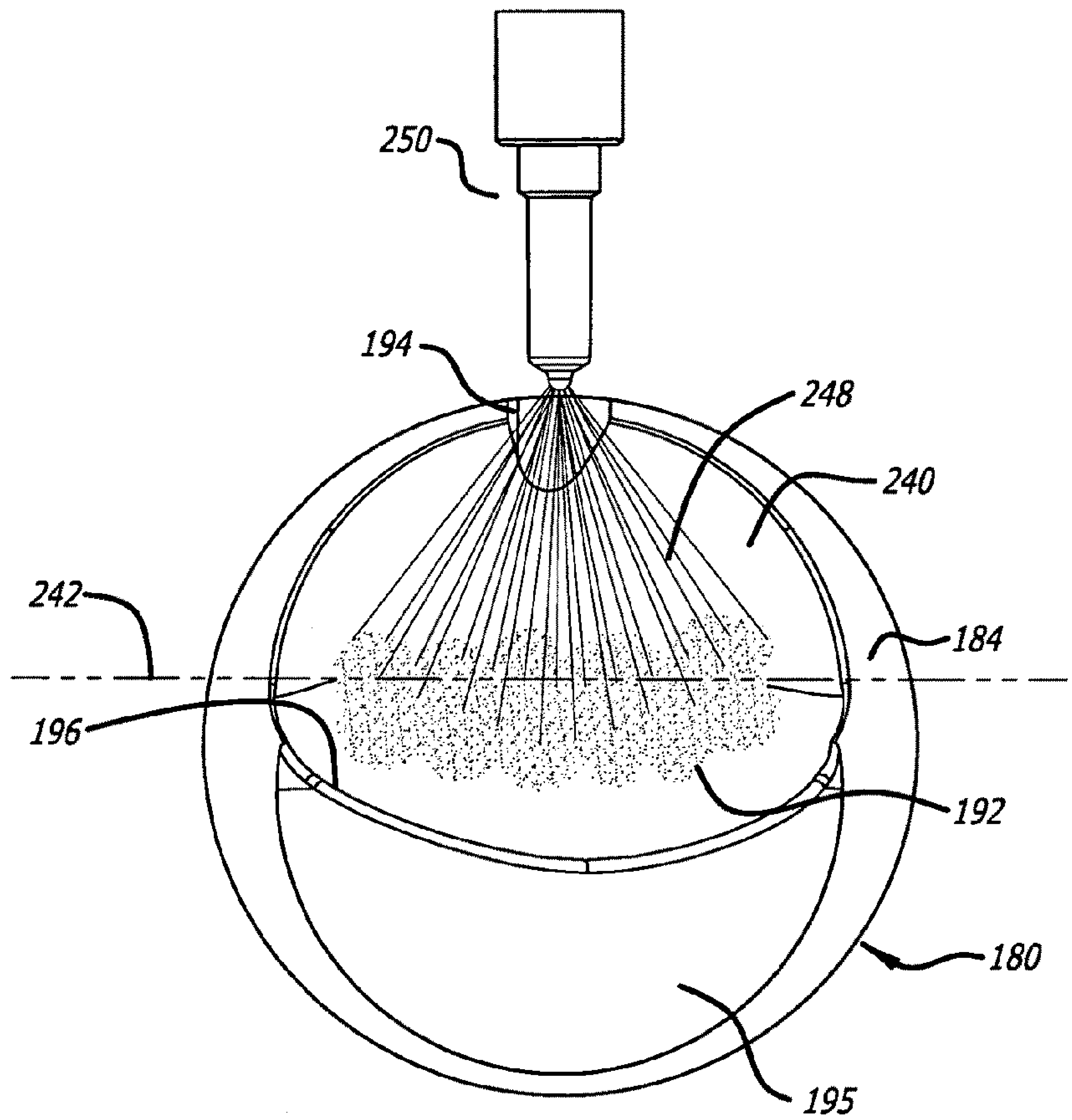


FIG. 10

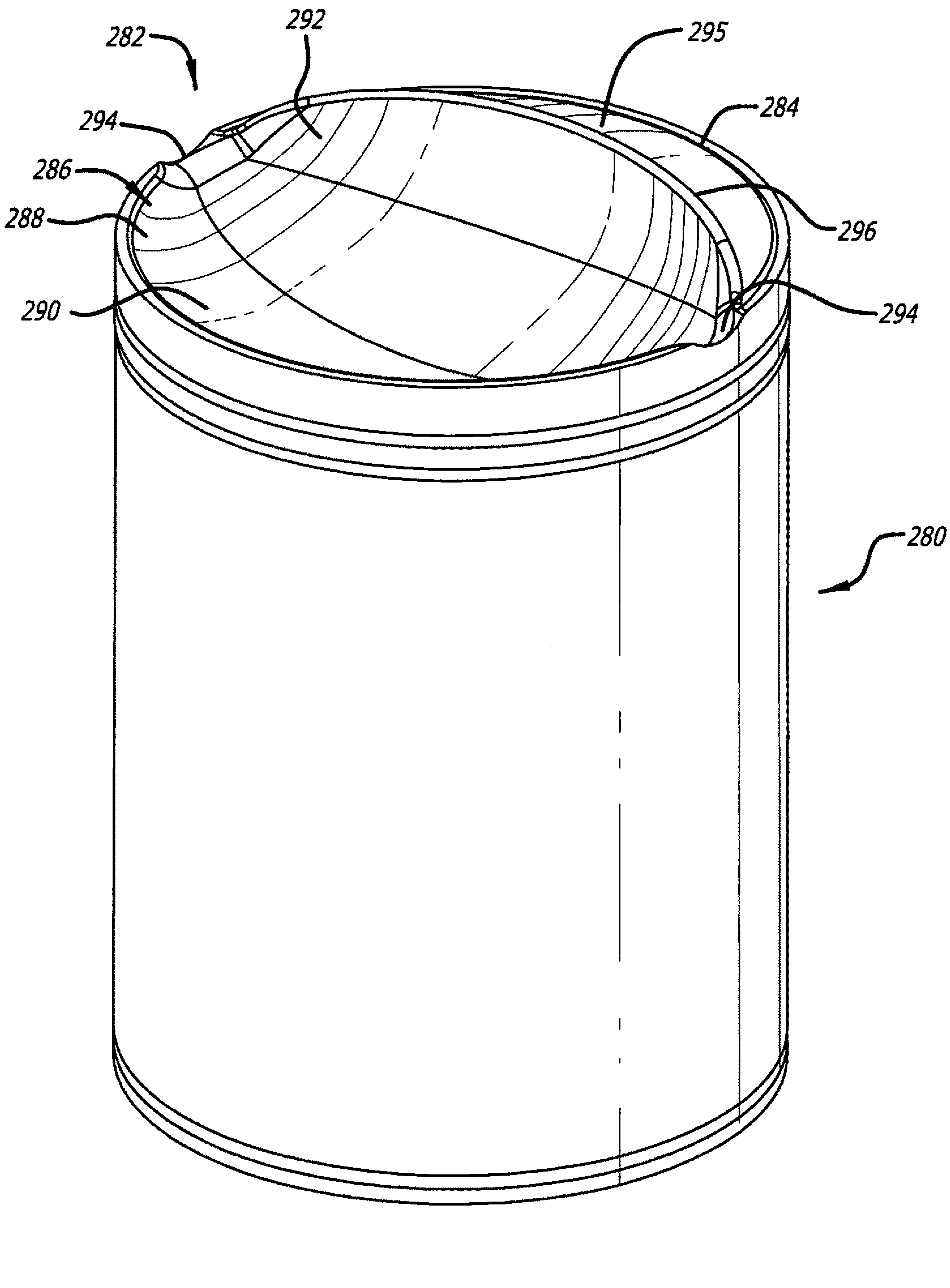


FIG. 11

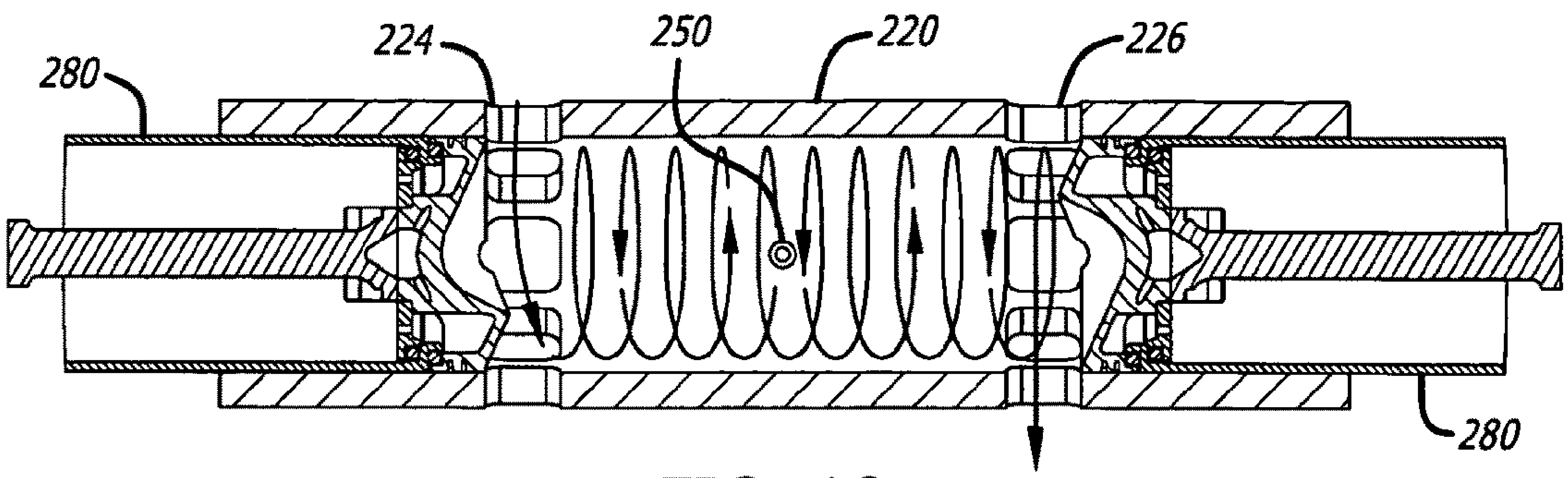


FIG. 12

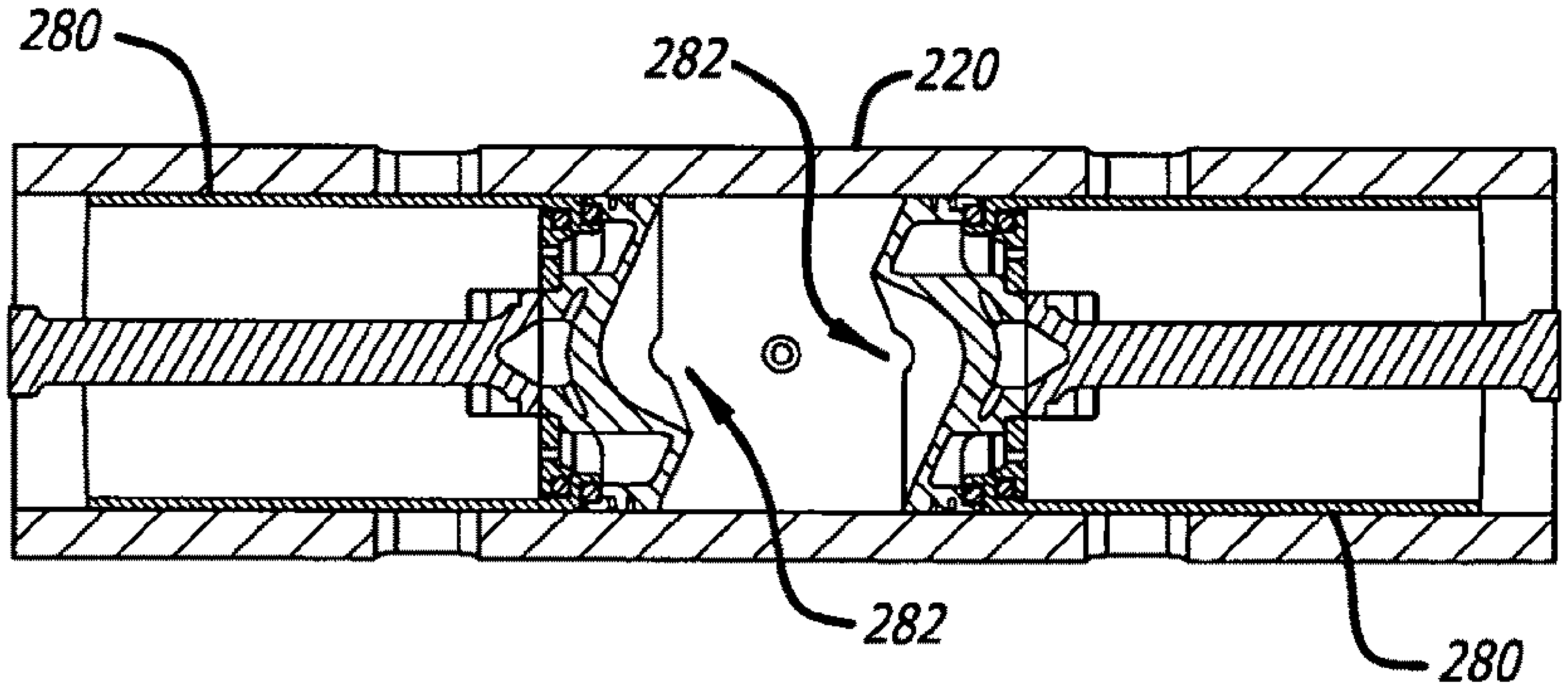


FIG. 13

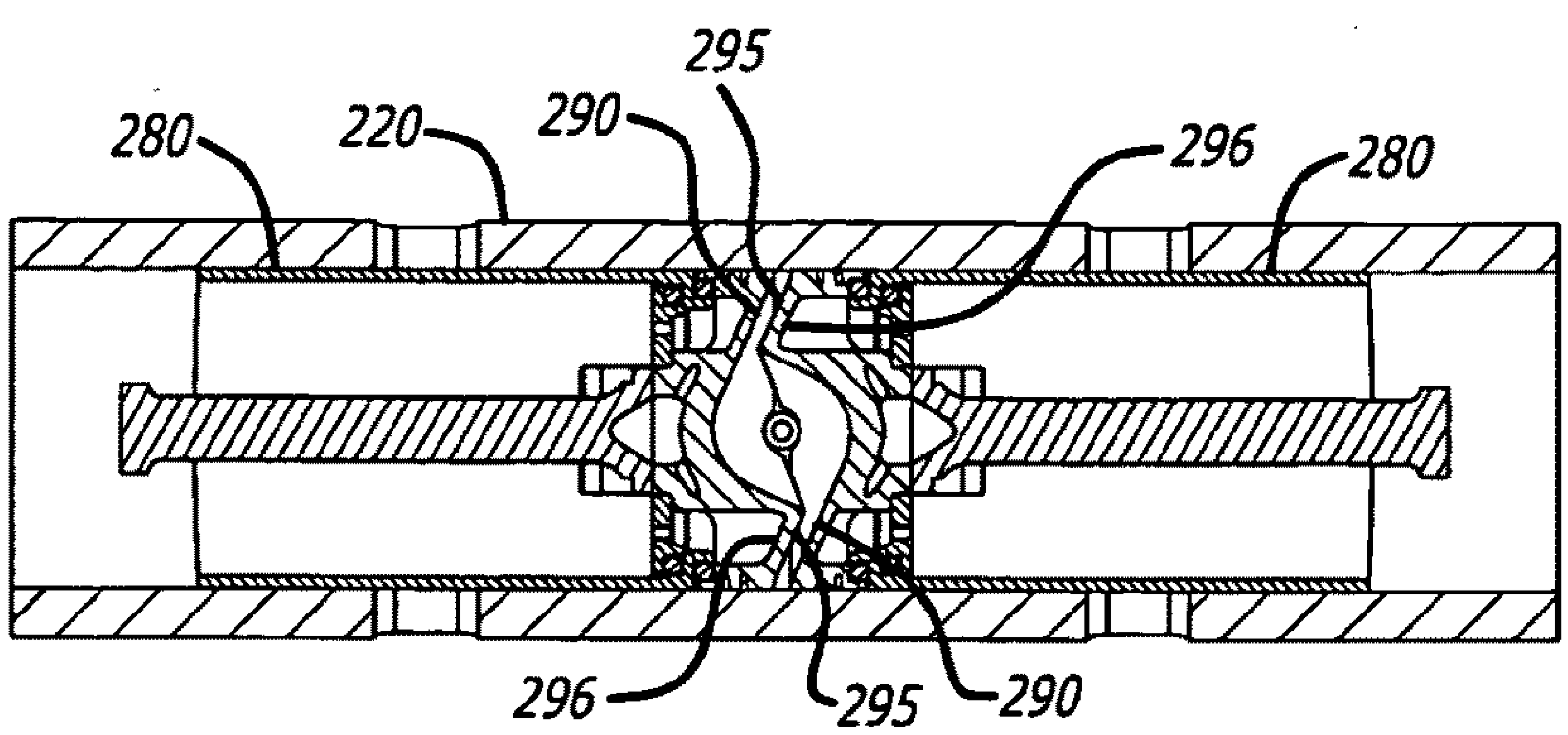


FIG. 14

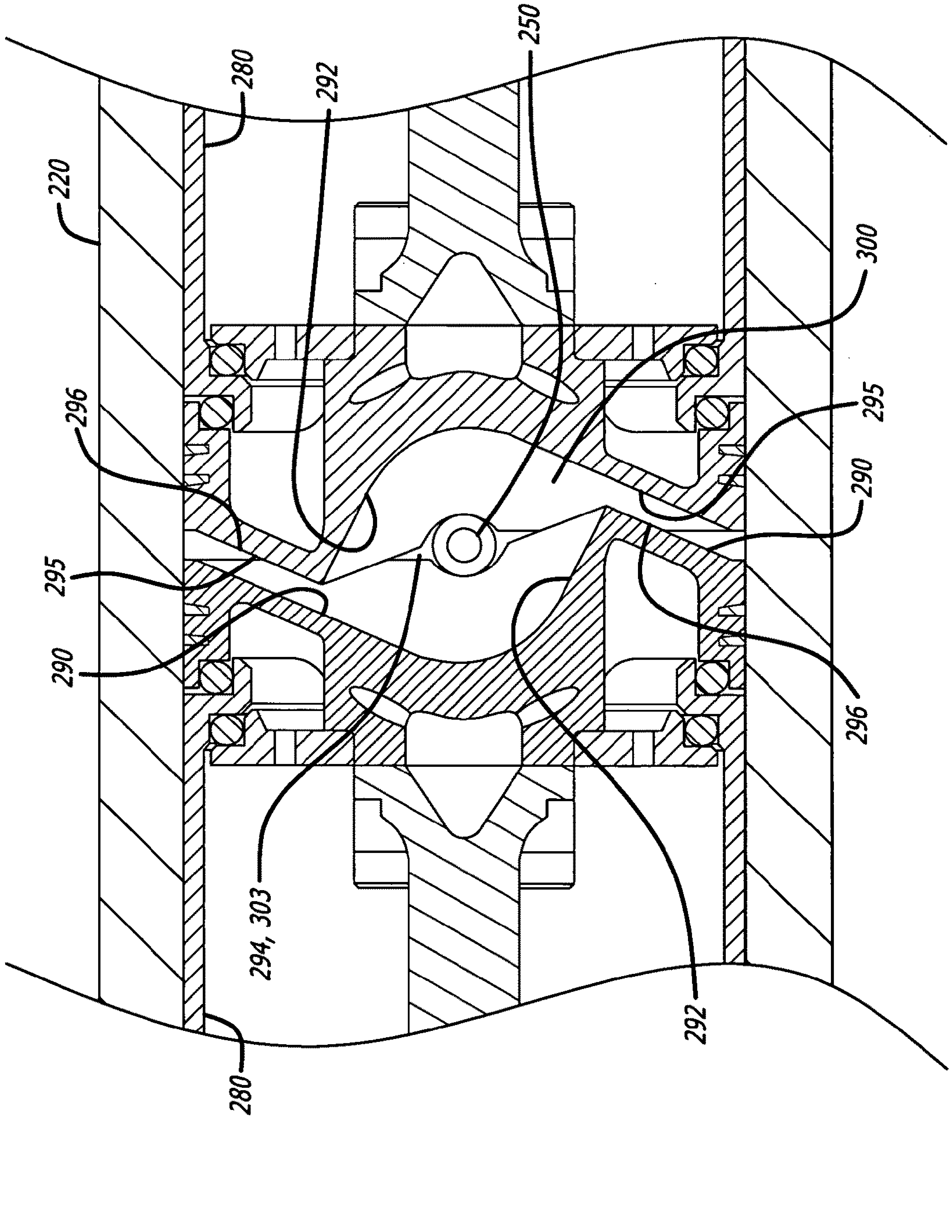
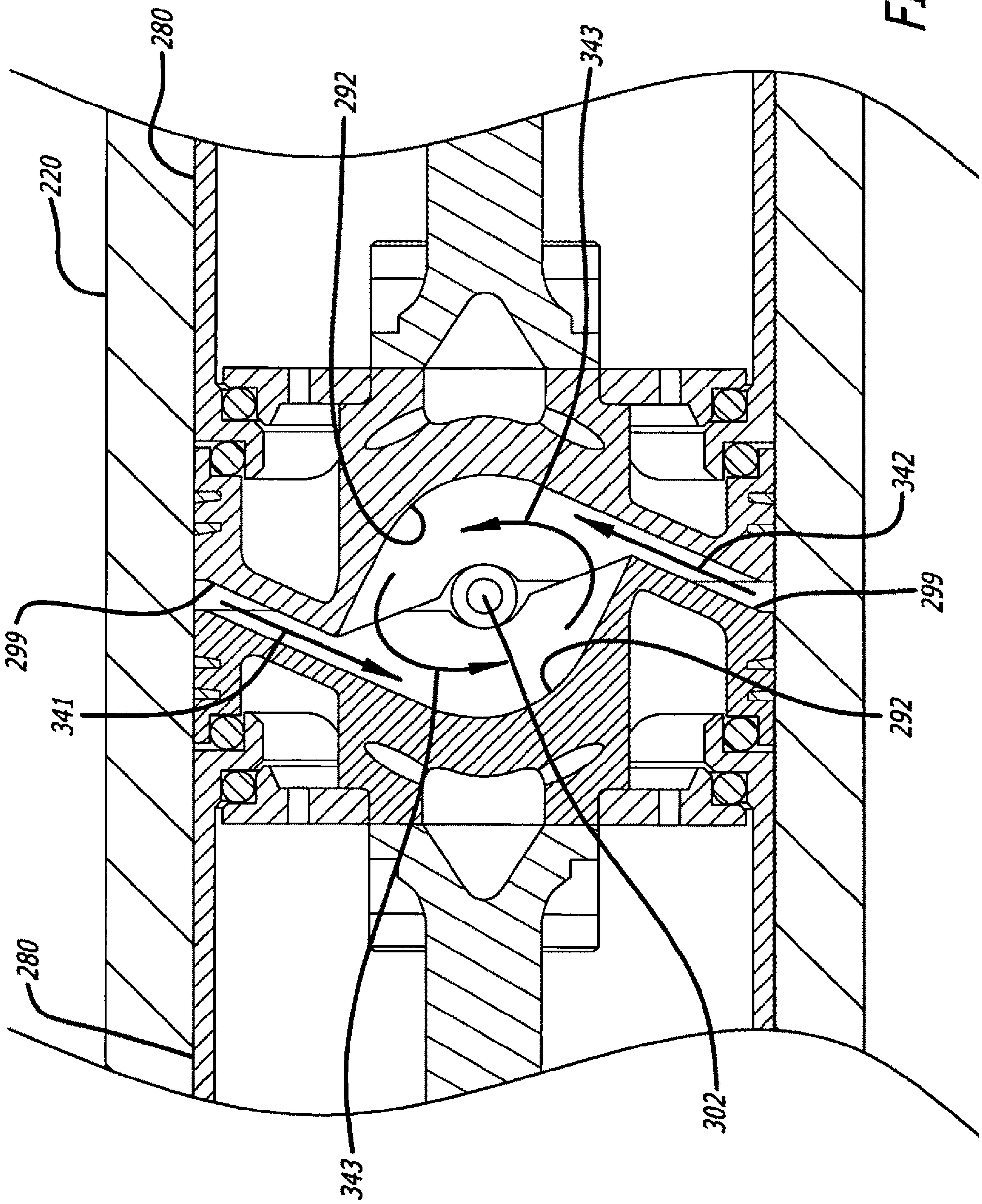
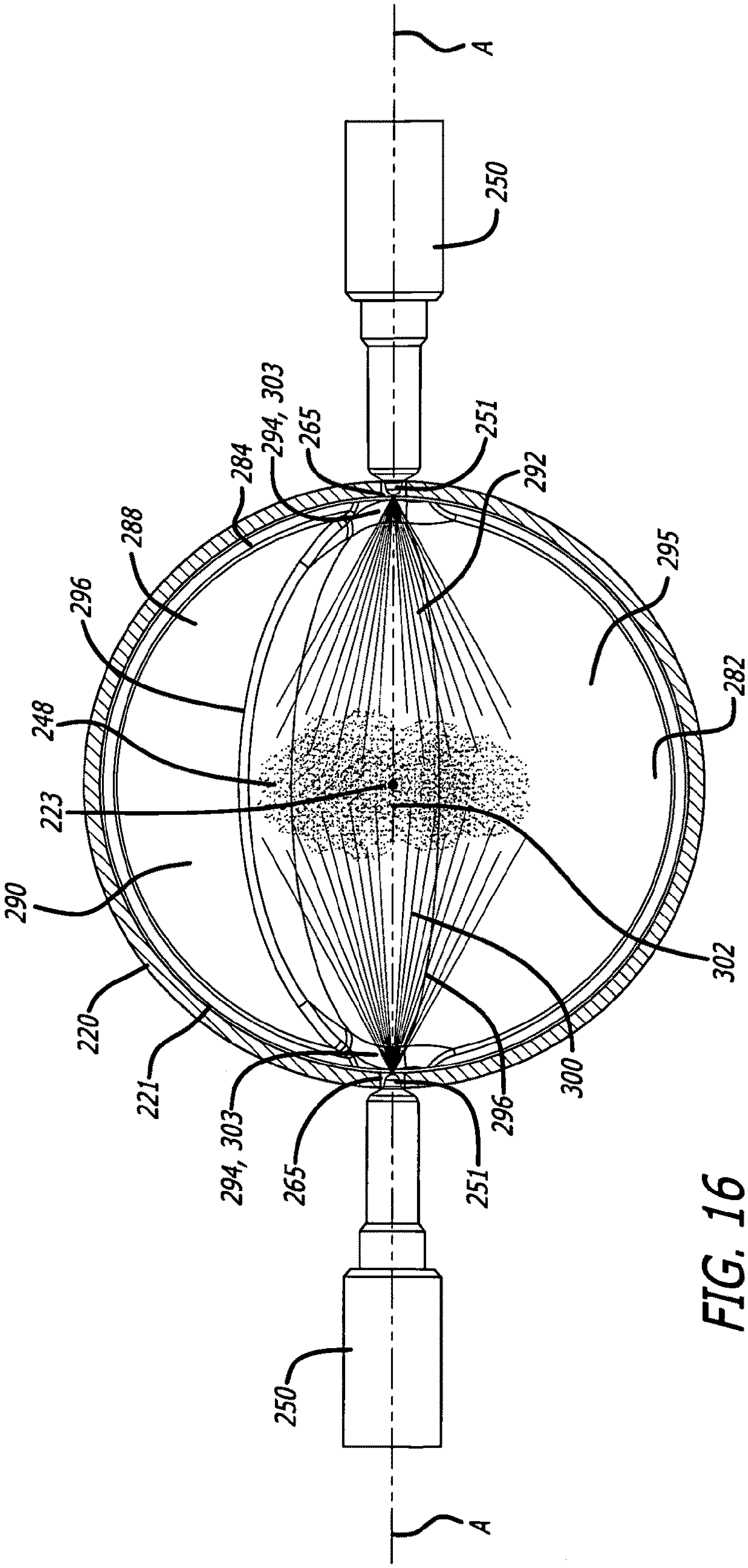


FIG. 15A

FIG. 15B




A
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302
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300
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265
251
250
A

FIG. 16

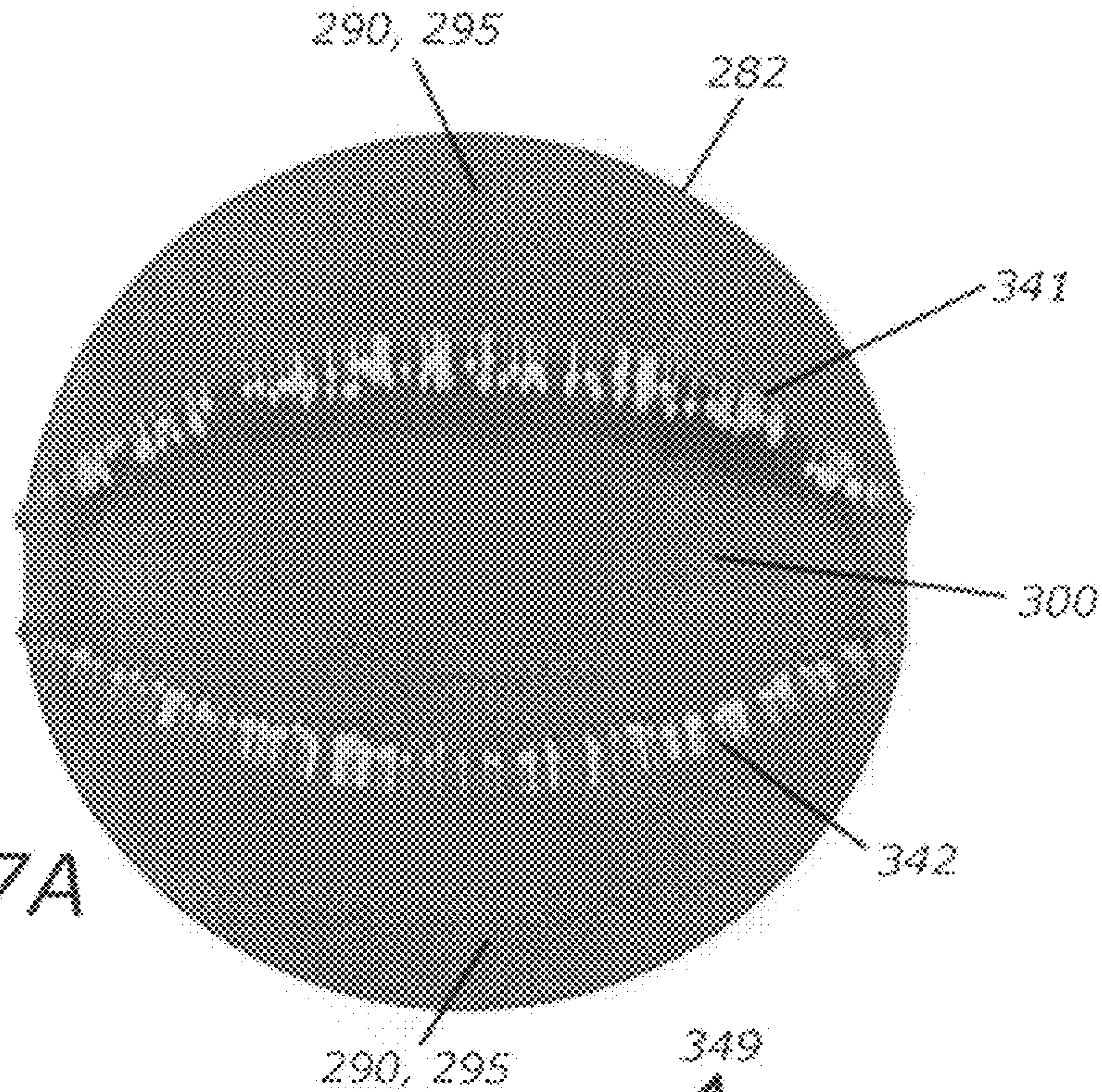

FIG. 17A

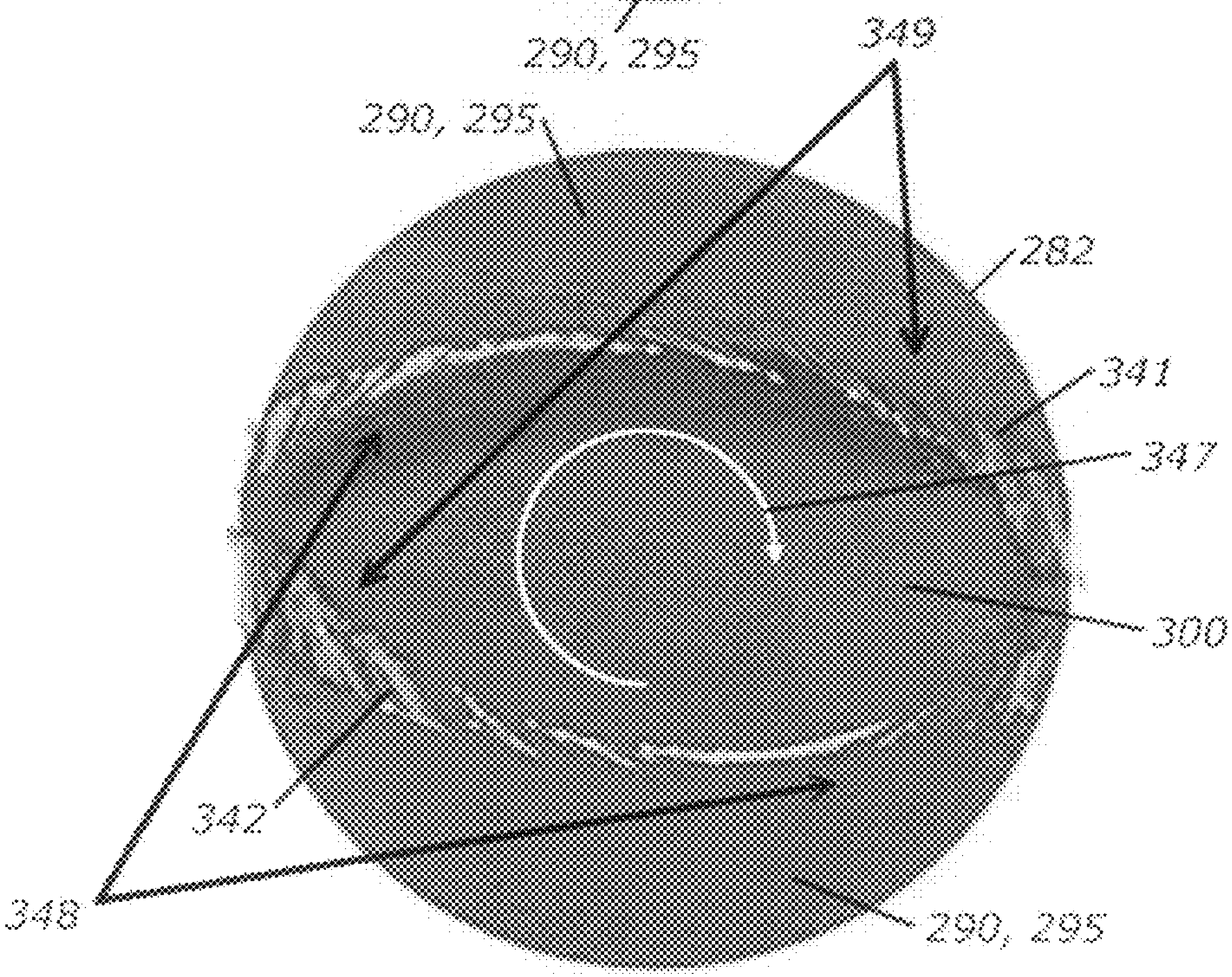

FIG. 17B

COMBUSTION CHAMBER CONSTRUCTIONS FOR OPPOSED-PISTON ENGINES

PRIORITY

This application claims priority to U.S. provisional application for patent 61/343,308, filed Apr. 27, 2010, to U.S. provisional application for patent 61/395,845, filed May 18, 2010, and to U.S. provisional application for patent 61/401,598, filed Aug. 16, 2010.

BACKGROUND

The field is combustion chambers for internal combustion engines. In particular, the field includes constructions for opposed-piston engines in which a combustion chamber is defined between end surfaces of pistons disposed in opposition in the bore of a ported cylinder. More particularly, the field includes opposed-piston engines with combustion chamber constructions that produce a tumbling motion in charge air admitted into the cylinder between the piston end surfaces.

Per FIG. **1**, an opposed-piston engine includes at least one cylinder **10** with a bore **12** and longitudinally-displaced intake and exhaust ports **14** and **16** machined or formed therein. One or more fuel injectors **17** are secured in injector ports (ports where injectors are positioned) that open through the side surface of the cylinder. Two pistons **20**, **22** according to the prior art are disposed in the bore **12** with their end surfaces **20***e*, **22***e* in opposition to each other. For convenience, the piston **20** is denominated as the "intake" piston because of its proximity to the intake port **14**. Similarly, the piston **22** is denominated as the "exhaust" piston because of its proximity to the exhaust port **16**.

Operation of an opposed-piston engine with one or more ported cylinders (cylinders with one or more of intake and exhaust ports formed therein) such as the cylinder **10** is well understood. In this regard, in response to combustion the opposed pistons move away from respective top dead center (TDC) positions where they are at their innermost positions in the cylinder **10**. While moving from TDC, the pistons keep their associated ports closed until they approach respective bottom dead center (BDC) positions where they are at their outermost positions in the cylinder. The pistons may move in phase so that the intake and exhaust ports **14**, **16** open and close in unison. Alternatively, one piston may lead the other in phase, in which case the intake and exhaust ports have different opening and closing times.

In many opposed piston constructions, a phase offset is introduced into the piston movements. As shown in FIG. **1**, for example, the exhaust piston leads the intake piston and the phase offset causes the pistons to move around their BDC positions in a sequence in which the exhaust port **16** opens as the exhaust piston **22** moves through BDC while the intake port **14** is still closed so that combustion gasses start to flow out of the exhaust port **16**. As the pistons continue moving away from each other, the intake piston **20** moves through BDC causing the intake port **14** to open while the exhaust port **16** is still open. A charge of pressurized air is forced into the cylinder **10** through the open intake port **14**, driving exhaust gasses out of the cylinder through the exhaust port **16**. As seen in FIG. **1**, after further movement of the pistons, the exhaust port **16** closes before the intake port **14** while the intake piston **20** continues to move away from BDC. Typically, the charge of fresh air is swirled as it passes through ramped openings of the intake port **14**. With reference to FIG. **1**, the swirling motion (or simply, "swirl") **30** is a generally helical movement of charge air that circulates around the cylinder's longitudinal axis and moves longitudinally through the bore of the cylinder **10**. Per FIG. **2**, as the pistons **20**, **22** continue moving toward TDC, the intake port **14** is closed and the swirling charge air remaining in the cylinder is compressed between the end surfaces **20***e* and **22***e*. As the pistons near their respective TDC locations in the cylinder bore, fuel **40** is injected into the compressed charge air **30**, between the end surfaces **20***e*, **22***e* of the pistons. As injection continues, the swirling mixture of air and fuel is increasingly compressed in a combustion chamber **32** defined between the end surfaces **20***e* and **22***e* as the pistons **20** and **22** move through their respective TDC locations. When the mixture reaches an ignition temperature, the fuel ignites in the combustion chamber, driving the pistons apart toward their respective BDC locations.

Turbulence is a desirable feature of charge air motion as fuel injection begins. Turbulence encourages the mixing of charge air with fuel for more complete and more uniform ignition than would otherwise occur. The geometries of the intake port openings and the cylinder of an opposed-piston engine provide a very effective platform for generation of a strong swirling motion of the charge air that promotes both removal of exhaust gasses (scavenging) and charge air turbulence. However, charge air motion that is dominated by swirl can produce undesirable effects during combustion. For example, during combustion in a cylindrical combustion chamber defined between flat piston end surfaces, swirl pushes the flame toward the cylinder bore, causing heat loss to the (relatively) cooler cylinder wall. The higher velocity vectors of swirl occur near the cylinder wall, which provides the worst scenario for heat losses: high temperature gas with velocity that transfers heat to the cylinder wall and lowers the thermal efficiency of the engine. The peripheries of the piston end surfaces also receive a relatively high heat load, which causes formation of a solid residue of oil coke that remains in the piston/cylinder interface when lubricating oil breaks down at high engine temperatures. Accordingly, in such opposed-piston engines, it is desirable to maintain charge air turbulence as injection starts while mitigating the undesirable effects produced by swirl.

In certain opposed-piston combustion chamber constructions, turbulence is produced by squish flow from the periphery of the combustion chamber in a radial direction of the cylinder toward the cylinder's axis. Squish flow is generated by movement of compressed air from a relatively high-pressure region at the peripheries of the piston end surfaces to a lower-pressure region generated by a bowl formed in at least one piston end surface. Squish flow promotes charge air turbulence in the combustion chamber. For example, U.S. Pat. No. 6,170,443 discloses a cylinder with a pair of opposed pistons having complementary end surface constructions. A circular concave depression formed in one end surface is symmetrical with respect to the axis of its piston and rises to a point in its center. The periphery of the opposing end surface has a convex shape in the center of which a semi-toridal (half donut-shaped) trench is formed. As the pistons approach TDC, they define a generally toroidally-shaped combustion chamber centered on the longitudinal axis of the cylinder. The combustion chamber is surrounded by a circumferential squish band defined between the concave and convex surface shapes. As the pistons approach TDC, the squish band generates an inwardly-directed squish flow into the toroidal trench and creates "a swirl of high intensity near top dead center." See the '443 patent at column 19, lines 25-27. Fuel is injected into the toridal combustion chamber in a radial direction of the bore.

Increasing the turbulence of charge air in the combustion chamber increases the effectiveness of air/fuel mixing. Domination of charge air motion by swirl or squish flow alone does achieve a certain level of turbulence. Nevertheless, it is desirable to create additional elements of charge air motion as injection commences in order to produce even more chaotic activity in the turbulence of the charge air, thereby to achieve better air/fuel mixing than can be obtained with swirl or squish alone.

SUMMARY

An aspect of an invention completed in respect of the objective described above is to have the piston end surfaces define a combustion chamber that creates a charge air motion component in addition to swirl and squish.

Another aspect of an invention completed in respect of the objective described above is to have the piston end surfaces define a combustion chamber that interacts with squish and swirl to produce one or more tumbling components in charge air motion in the combustion chamber.

Preferably, the tumbling motion is a rotating movement of charge air that is transverse to and circulates across the longitudinal axis of the cylinder. Preferably, the tumbling motion is a circulation of charge air that circulates around a diameter of the cylinder bore.

In a preferred construction, a combustion chamber defined between the opposing end surfaces is bordered by a squish zone that defines at least one squish flow path that is skewed with respect to the cylinder bore. Preferably, the combustion chamber is defined by a bowl formed in at least one piston end surface. In some instances, the bowl is clam-shell-shaped. In other instances the bowl has the shape of an elongated tapered cylinder. In some aspects, the bowl has an elongated ellipsoidal shape.

In another preferred construction, a combustion chamber is defined by the end surfaces of the opposed pistons at TDC, in which one piston end surface has a circumferential area centered on the longitudinal axis of the piston, and a bowl within the circumferential area and the other piston end surface is flat. Preferably, the combustion chamber is clam-shell-shaped.

In another preferred construction, a combustion chamber is defined between end surfaces of the opposed pistons, in which each piston end surface has a circumferential area centered on the longitudinal axis of the piston, and a bowl within the circumferential area that defines a concave surface with a first portion curving inwardly from a plane containing the circumferential area toward the interior of the piston and a second portion curving outwardly from the interior of the piston through the plane containing the circumferential area. Preferably, the combustion chamber has the shape of an elongated ellipsoid.

In still another preferred construction, a method is provided for operating an internal combustion engine including at least one cylinder with longitudinally-separated exhaust and intake ports, and a pair of pistons disposed in opposition for reciprocating in a bore of the cylinder, by forming a combustion chamber having an elongated ellipsoidal shape between the end surfaces of the pistons as the pistons move toward respective TDC positions, generating squish flows of charge air having a direction that is skewed with respect to a major axis of the combustion chamber, generating at least one tumbling motion of charge air in the combustion chamber in response to the squish flow and swirling charge air, and injecting fuel into the combustion chamber.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a side sectional partially schematic drawing of a cylinder of an opposed-piston engine with prior art opposed pistons near respective bottom dead center locations, and is appropriately labeled "Prior Art".

FIG. **2** is a side sectional partially schematic drawing of the cylinder of FIG. **1** with the prior art opposed pistons near respective top dead center locations where flat end surfaces of the pistons define a prior art combustion chamber, and is appropriately labeled "Prior Art".

FIG. **3** is a side schematic view of a pair of opposed pistons in which the end surfaces of the pistons define a first combustion chamber construction.

FIG. **4** is an end view of one of the pistons of FIG. **3** showing an end surface with a bowl formed therein.

FIGS. **5** and **6** are elevational perspective views of respective pistons of a pair of pistons in which the end surfaces of the pair of pistons are formed to define a second combustion chamber construction.

FIGS. **7-9** are side sectional drawings showing an operational sequence of an opposed-piston engine including a pair of pistons according to FIGS. **5** and **6**.

FIG. **9**A is an enlarged view of a portion of FIG. **9** showing in greater detail the second combustion chamber construction.

FIG. **10** is an end view of the piston of FIG. **5** showing a piston end surface with a bowl formed therein and a pattern of fuel injection.

FIG. **11** is an elevational perspective view of a piston of a pair of pistons in which identical end surfaces of the pair of pistons are formed to define a third combustion chamber construction.

FIGS. **12-14** are side sectional drawings showing an operational sequence of an opposed-piston engine including a pair of pistons according to FIG. **11**.

FIG. **15**A is an enlarged view of a portion of FIG. **14** showing in greater detail the third combustion chamber construction.

FIG. **15**B is the enlarged view of FIG. **15**A showing squish and tumble air flows in the third combustion chamber construction

FIG. **16** is an end view of one of the pistons of FIG. **11** showing an end surface with a bowl formed therein and a pattern of fuel injection.

FIGS. **17**A and **17**B are schematic illustrations of the piston end surface view of FIG. **16** showing interaction between the end surface and squish flow, without swirl (FIG. **17**A), and with swirl (FIG. **17**B).

DETAILED DESCRIPTION OF THE PREFERRED CONSTRUCTIONS

In the combustion chamber constructions to be described, an internal combustion engine includes at least one cylinder with longitudinally-separated exhaust and intake ports; see, for example, the cylinder **10** illustrated in FIGS. **1** and **2**. A pair of pistons is disposed in opposition in a bore of the cylinder and a combustion chamber structure is defined between the opposing end surfaces of the pistons as the pistons move toward top dead center positions. A circumferential area defines a periphery on each of the end surfaces. The combustion chamber includes a cavity defined between the end surfaces, and has at least one opening through which fuel is injected (hereinafter an "injection port") that extends at least generally in radial direction of the cylinder and opens into the cavity.

During operation of the internal combustion engine, as the pistons approach TDC, one or more squish zones direct flows of compressed air (called "squish flows") into the combustion chamber in at least one direction that is skewed with respect to a diametrical direction of the bore. This process is referred to as "generating squish". The portions of the end surfaces that generate squish are referred to as squish surfaces, and channels defined between the squish surfaces are referred to as squish channels. Squish flow is deflected or redirected by one or more curved surfaces in a combustion chamber cavity into at least one tumble motion that circulates in the cavity.

In the following descriptions, "fuel" is any fuel that can be used in an opposed-piston engine. The fuel may be a relatively homogeneous composition, or a blend. For example, the fuel may be diesel fuel or any other fuel ignitable by compression ignition. Further, the descriptions contemplate ignition resulting from compression of an air/fuel mixture; however it may be desirable to provide additional mechanisms, such as glow plugs, to assist compression ignition. The descriptions contemplate injection of fuel into a compressed gas in a combustion chamber when opposed pistons are at or near TDC locations. The gas is preferably pressurized ambient air; however, it may include other components such as exhaust gases or other diluents. In any such case, the gas is referred to as "charge air."

First combustion chamber construction: FIG. **3** is a schematic diagram of a pair of opposed pistons with end surfaces that define a first combustion chamber construction as the pistons approach respective TDC locations. The cylinder in which the pistons are disposed is represented by an axis with which the axes of the pistons are collinear. The combustion chamber includes one piston end surface shaped to produce a tumbling motion that curves across the cylinder's axis. This construction includes a squish zone in which a curved cavity between the end surfaces redirects air flowing toward the center of the squish zone into a tumbling motion. The cavity is defined by a bowl formed in, a portion of the end surface of one of the pistons; preferably, but not necessarily, that piston is the intake piston. A flat peripheral portion of the end surface surrounds the bowl. An injection port opens into the bowl, through the peripheral portion. Preferably, but not necessarily, the injection port is oriented in a direction radial to the piston. The opposing piston (preferably, the exhaust piston) has a flat, essentially planar end surface. Air is compressed between the flat portions of the piston end surfaces, creating a high velocity squish flow of compressed air moving into the bowl in a radial direction of the cylinder. A portion of the squish flow is deflected or redirected from the radial direction, along the curved surface of the bowl, to generate a tumble flow in the combustion chamber that circulates across the axis of the cylinder. Preferably, fuel is injected in the same direction as the tumble motion so that the fuel can be conveyed by the tumbling air movement. If the charge air is initially swirled when entering the cylinder through an intake port (not shown), the motion of the charge air in the combustion chamber includes elements of swirl, squish, and tumble.

In FIG. **3**, the intake piston **105** and the exhaust piston **106** are at or near respective TDC positions in a cylinder with an axis **135**. As per FIG. **4**, the intake piston **105** has an end surface **110** in which an irregularly-shaped, non-circular bowl **120** is formed. In some aspects, the bowl **120** has the shape of a clam shell. The bowl **120** is offset towards a periphery portion of the end surface **110** in which a notch **130** constituting an injection port is formed. The bowl **120** is substantially surrounded by a large flat peripheral surface area **140** of varying width. The bowl has a concave surface **121** curving inwardly from a plane containing the surface area **140**, toward the interior of the piston **105**. The concave surface is asymmetrical. More particularly, as seen in FIG. **3**, the concave surface **121** has a hook-like shape in cross section that transitions from a first level near the notch **130**, to a second level, deeper into the piston than the first level, near the center of the piston, and then doubles back through an undercut portion **122** that curves back in the direction of the notch **130** to a lip **123**. The end surface **111** of the exhaust piston **106** is essentially planar, with no bowl.

With further reference to FIG. **3**, with the pistons **105** and **106** approaching their respective TDC locations, air in the cylinder is compressed in the shrinking space between the end surfaces **110** and **111** and is, entrained in a radial squish flow toward the axis **135** of the cylinder. As radially-moving squish flow enters the bowl **120**, it encounters the curved bowl surface **121**. The curved bowl surface **121** redirects radially-moving squish flow into a direction that is skewed with respect to the radial direction. As the now-skewed squish flow crosses the cylinder axis **135**, it encounters the sharp backward curve of the undercut portion **122** and curves back toward the lip **123** which imparts a tumbling motion **136** in which the air circulates transversely across the axis **135**. Fuel is injected into the tumbling air by way of the notch **130**. It is desirable that the squish gap (d), that is, the distance between the flat areas of the piston end surfaces at TDC, be very small; for example, we have designed the end surfaces for a squish gap 0.2 mm to 0.5 mm. A very small squish gap forces the compressed air into the bowl **120** at very high velocity and energy levels to create the desired tumble at the beginning of, and during, injection.

Second combustion chamber construction: FIGS. **5**-**9**, **9**A, and **10** illustrate a second combustion chamber construction in which the squish surface areas are increased with respect to those of the first construction so as to provide a relatively greater squish flow velocity and create a relatively stronger squish flow motion in order to facilitate more complete mixing of fuel and gas than the first construction. The cavity is defined between bowls with concave surfaces that are formed in the opposing piston end surfaces. In this regard, a bowl with a protruding side is formed in the end surface of each of the opposed pistons, and the pistons are rotationally oriented in the cylinder to place complementarily concave/convex surfaces of the bowls in opposition to one another. The complementary concave/convex surface portions define squish channels that are skewed in different directions with respect to a diametrical direction of the cylinder. Preferably, although not necessarily, the combustion chamber cavity defined between these two end surfaces is an elongated, irregularly-shaped cylinder that tapers toward each end. The closed, continuously-curved geometry of the combustion chamber and the oppositely-skewed squish flows create and sustain a tumble motion that circulates across the cylinder axis. We have calculated that this combustion chamber structure can provide up to a 3.5 times higher tumble ratio than the first construction.

In the second construction, an injection port is positioned along the periphery of the combustion chamber, and is oriented generally transversely to a combustion chamber major axis, allowing for a wide spray arrangement that can be produced by an injector nozzle with a large number of holes. Preferably, the injection port is oriented at least generally radially or perpendicularly to the major axis.

In FIG. **5**, the intake piston **180** has an end surface **182** with a flat circumferential area **184** centered on the longitudinal axis of the piston **180**. The flat circumferential area **184** defines a periphery of the end surface **182**. A bowl **186** is formed within the periphery. The bowl **186** has a concave surface **188** with a first portion **190** curving inwardly from a plane containing the flat peripheral area **184** and toward the interior of the piston **180**, and a second portion **192** curving outwardly from the interior of the piston through the plane containing the flat peripheral area **184**. A notch **194** extends radially through the periphery into the bowl **186**. The end surface **182** further includes a convex surface **195** within the periphery that curves outwardly from the plane containing the flat circumferential area **184**. The convex surface **195** meets the second portion **192** of the concave surface **188** to form a ridge **196** that protrudes outwardly from the end surface **182**.

As per FIG. **6**, the exhaust piston **200** has an end surface **202** with a flat circumferential area **204** centered on the longitudinal axis of the piston **200**. The flat circumferential area **204** defines a periphery of the end surface **202**. A bowl **206** is formed within the periphery. The bowl **206** is offset from the longitudinal axis of the piston **200**. The bowl **206** has a concave surface **208** with a first portion **210** curving inwardly from a plane containing the flat circumferential area **204** toward the interior of the piston **200**, and a second portion **212** curving outwardly from the interior of the piston through the plane containing the flat circumferential area **204**. The end surface **202** further includes a convex surface **215** within the periphery that curves outwardly from the plane containing the flat circumferential area **204**. The convex surface **215** meets the second portion **212** of the concave surface **208** to form a ridge **216** that protrudes outwardly from the end surface **202**. A notch **214** extends through the periphery and the ridge **216** into the bowl **206**.

The ridge **196** seen in FIG. **5** is substantially higher with respect to the end surface **182** of the intake piston than the ridge **216** seen in FIG. **6** is to the end surface **202** of the exhaust piston. The ridge **196** is also more centrally located with respect to the central axis of the piston **180** than the ridge **216** is to the axis of the piston **200**. These asymmetries give the squish zone and the combustion chamber of the second construction somewhat asymmetrical shapes.

Referring now to FIG. **7**, the two pistons **180** and **200** are shown at or near respective BDC locations within a cylinder **220**. The pistons are rotationally oriented in the bore of the cylinder **220** so as to align the notches **194**, **214** with one another. Air is directed through the intake port **224** into the cylinder **220** as exhaust products flow out of the cylinder through the exhaust port **226**. As the pistons move from BDC toward TDC as per FIG. **8**, the ports are closed and the air in the cylinder is increasingly compressed between the end surfaces **182** and **202**. With reference to FIGS. **8**, **9**, and **9**A, as the pistons approach TDC, compressed air is squished between the convex surface **195** of the ridge **196** and the concave surface portion **210**, and is also squished between the convex surface **215** of the ridge **216** and the concave surface portion **190**. The squished air flows into combustion chamber space **240** defined between the end surfaces **182** and **202** where it is deflected by the concave surface portions **192** and **212** into a tumble motion **228**. As is evident from FIGS. **9** and **9**A, when the pistons **180** and **200** move through their respective TDC locations, the surfaces **196** and **216** mesh with the opposing concave surface portions **210** and **190** give the combustion chamber space **240** the shape of an irregular cylinder.

As seen in FIGS. **9**A and **10**, the injection port defined by the notches **194** and **214** is positioned along the periphery of the combustion chamber space **240** and is oriented generally radially to the pistons or transversely to a combustion chamber major axis **242**, allowing for a wide spray plume **248** produced by an injector nozzle **250**. Preferably, the injection port is oriented radially with respect to the pistons **180** and **200** or perpendicularly to the major axis **242**. The fuel **248** injected into the combustion chamber space **240** by the injector nozzle **250** is deflected by the concave surface portion **192** into mixture with the tumbling air, thus keeping the air/fuel mixture well within the combustion chamber space **240** and away from the cylinder wall.

Third combustion chamber construction: FIGS. **11**-**14**, **15**A, **15**B, and **16** illustrate a third combustion chamber construction defined by complementary end surface structures of opposed pistons disposed in a ported cylinder of an opposed piston engine. The third combustion chamber construction is bordered by squish surface areas that are larger than the squish areas of both the first and second constructions so as to provide a relatively greater squish flow velocity and create a relatively stronger squish flow motion than do the first and second constructions. Identical generally symmetrical bowls are formed in the end surfaces of the opposed pistons, and the pistons are rotationally oriented to place complementary curved surfaces of the bowls in opposition in order to maximize the squish surface areas of the squish zone.

The end surface structure of each piston has a periphery surrounding a bowl defining a concave surface. The concave surface includes a first portion curving away from a plane containing the periphery surface toward the interior of the piston and a second portion curving away from the first portion and protruding outwardly in part from the plane. A convex surface opposite the bowl curves away from the periphery and protrudes outwardly from the plane. The convex surface meets the second portion of the concave surface to form a ridge therewith. Preferably, but not necessarily, the bowl has a semi-ellipsoidal shape. The end surface structure is provided on both pistons and the pistons are disposed in the bore of a ported cylinder with their end surfaces oriented to place complementary curved surfaces of the end surface structures in opposition in order to define a combustion chamber. Preferably, but not necessarily, the combustion chamber space defined between these two end surfaces is, or is very close to, an elongated ellipsoidal cylinder, providing a generally symmetrical geometry to reinforce and sustain the tumble motion. It is estimated that this combustion chamber structure provides a tumble ratio double that of the second construction. In the third construction, it is desirable that at least one injection port be positioned on a major axis of the combustion chamber.

The structures of the piston end surfaces that define the third construction are essentially identical to each other; accordingly, the piston **280** shown in FIG. **11** represents both the intake piston and exhaust piston. The piston **280** has an end surface **282**. A flat circumferential area **284** centered on the longitudinal axis of the piston **280** defines a periphery of the end surface **282**. A bowl **286** is formed within the periphery. The bowl **286** has a concave surface **288** with a first portion **290** curving inwardly from a plane containing the flat circumferential area **284**, toward the interior of the piston **280**, and a second portion **292** curving outwardly from the interior of the piston through the plane. The end surface **282** further includes a convex surface **295** within the periphery that curves outwardly from the plane. The convex surface **295** meets the second portion **292** of the concave surface **288** to form a ridge **296** that protrudes outwardly from the end surface **282**. At least one notch **294** extends through the periphery into the bowl **286**; preferably two aligned notches **294** are provided.

Referring now to FIG. **12**-**14**, the two pistons **280** having end surfaces shaped as per FIG. **11** are shown at or near respective BDC locations within the ported cylinder **220**. The pistons are rotationally oriented in the bore of the cylinder **220** so as to align the end surfaces in complement; that is to say, the concave surface portion **290** of one piston **280** faces the convex surface **295** of the other piston. Charge air is forced through the intake port **224** into the cylinder, as exhaust products flow out of the cylinder through the exhaust port **226**. For purposes of scavenging and air/fuel mixing, the charge air is swirled as it passes through the intake port **224**. As the pistons **280** move from BDC toward TDC as per FIG. **13**, the intake and exhaust ports **224** and **226** close and the swirling charge air is increasingly compressed between the end surfaces **282**. With reference to FIGS. **15**A and **15**B, as the pistons **280** approach TDC, compressed air flows from the peripheries of the end surfaces through squish channels **299** defined between the concave-convex surface pairs **290**, **295**. These squish airflows flow into a combustion chamber **300** having a cavity defined between the end surface bowls. At the same time, compressed charge air nearer the longitudinal axis of the cylinder continues to swirl. As the pistons **280** move through their respective TDC locations, the opposing concave-convex surfaces **290**, **295** mesh with one another to give the combustion chamber cavity an elongated, generally ellipsoidal shape. Opposing pairs of notches **294** (see FIG. **11**) in the end surfaces **282** define injection ports **303** (see FIG. **15**A) that open into the combustion chamber **300** at opposing pole positions of the ellipsoidal shape. As per FIG. **16**, the elongated, ellipsoidal shape has a major axis **302** that extends between the opposing pole positions. In other words, the injection ports **303** are aligned along the major axis **302**.

Interactions between the end surfaces **282** and charge air are illustrated in FIGS. **17**A and **17**B. FIG. **17**A shows squish flows into the combustion chamber **300** without charge air swirl; FIG. **17**B illustrates how the squish flows affect and are affected by swirl. As the pistons move toward TDC, squish regions (between opposing concave-convex surface pairs **290**, **295**) produce locally high pressure that directs squish flows of charge air into the central region of the combustion chamber **300**. In this regard, with reference to FIGS. **15**A, **15**B and **17**A, at the start of injection, when the pistons are near their respective TDC locations, the concave-convex surface pairs **290**, **295** generate squish flows **341**, **342** into the combustion chamber **300**. As illustrated in FIG. **15**B, these squish flows are oppositely-directed, parallel, and skewed with respect to the major axis **302**. This spatial relationship causes generation of a tumbling motion **343** when the squish flows encounter the outwardly-directed end surface portions **292**. In this regard, a tumbling motion is a circulating motion of charge air in the combustion chamber that is at least generally transverse to the longitudinal axis of the cylinder; in the case of the tumbling motion **343**, the circulation is generally around the major axis **302**. As per FIG. **17**B, when swirl **347** is added to charge air motion, the swirling motion, depending on its intensity, counteracts or overcomes squish flow in the combustion chamber regions **348**, and enhances the squish flow at the interface between the combustion chamber regions **349**. These swirl-plus-squish interactions generate a more intense tumbling motion around the major axis **302** than do the squish flows alone. Modeling indicates that as the intensity of the initial swirl is increased, the intensity of this tumbling motion produced near TDC also increases. In addition, the swirl-plus-squish interactions with the end surfaces of the pistons in the combustion chamber **300** produce a second tumbling motion about an axis that is orthogonal to the major axis. For example, such an axis corresponds to, or is generally parallel to, the equatorial diameter of the elongated ellipsoidal shape. Thus, at the start of injection, the turbulent motion of the charge air in the combustion chamber **300** includes a swirl component, incoming squish flows, and tumble components about orthogonal tumble axes

With reference to FIGS. **15**A, **15**B, and **16**, fuel **248** is injected into the tumbling air in the combustion chamber space **300** by opposed injectors **250**. According to the third construction, the combustion chamber is essentially centered with respect to the longitudinal axes of the cylinder and the pistons. When the pistons are near TDC, at least one pair of aligned notches **294** defines at least one injection port **303** opening into the combustion chamber cavity **300**. The at least one injection port **303** is located at or near one end of the combustion chamber, aligned with the major axis **302** thereof, so that the fuel plume **248** is confined between and guided by the opposing concave surface portions **292**. Preferably, two injection ports are provided at each end of the combustion chamber cavity **300**, aligned with the major axis thereof, and fuel is injected from two opposing injectors **250** through the injection ports.

In some aspects, it is desirable to inject at least one spray of fuel into a combustion chamber having an elongated ellipsoidal shape. It is preferable, however, to inject a pair of opposing sprays of fuel into the turbulent charge air motion generated in the combustion chamber by swirl-plus-squish interactions, where the opposing sprays meet in the combustion chamber and form a cloud of fuel that is well mixed with the compressed charge air due to the turbulence. With reference to FIG. **16**, the view is a sectional one at or near the longitudinal midpoint of the cylinder **220**, looking directly into the cylinder's bore **221** toward a piston end surface **282** disposed in the bore at a position where it and the unseen piston end surface define the combustion chamber **300**. The cylinder's axis is indicated by reference numeral **223**. According to the third construction, the combustion chamber **300** is essentially centered longitudinally with respect to the cylinder's axis **223**. Fuel injectors **250** are positioned with their nozzle tips **251** disposed at injector ports **265**. Each injector nozzle tip has one or more holes through which fuel **248** is injected through a respective injector port, into the combustion chamber **300**. Preferably, each injector tip **251** sprays fuel **248** in a diverging pattern that is aligned with and travels through an injection port **303** along the major axis **302** of the ellipsoidal combustion chamber **300**, into the central portion of the combustion chamber **300**. Preferably, opposing spray patterns of fuel are injected into the turbulent air motion in the combustion chamber **300**. In some aspects, the opposing spray patterns meet at or near the center of the combustion chamber and form a cloud of fuel droplets that are mixed with charge air having a complex turbulent motion that includes swirl, squish, and tumble components. Preferably, but not necessarily, the fuel injectors **250** are disposed such that their axes A are in alignment with each other and a diametrical direction of the bore **221**. This causes the injector tips to be oriented in opposition along a diameter of the cylinder **220** that is aligned with the major axis **302**.

The combustion chamber constructions illustrated and described hereinabove are intended to be utilized in opposed-piston combustion-ignition engines which impose swirl on the charge of air forced into the cylinder. Nevertheless, the combustion chamber construction can be utilized in those opposed-piston combustion-ignition engines that do not swirl the charge air.

The pistons and associated cylinder are manufactured by casting and/or machining metal materials. For example, the pistons may be constituted of a skirt assembled to a crown on which a piston end surface is formed. As a further example, but without excluding other materials, the crown may comprise a high carbon steel such as 41-40 or 43-40, and the skirt may be formed using 4032-T651 aluminum. In such cases, the cylinder preferably comprises a cast iron composition.

Although the invention has been described with reference to preferred constructions, it should be understood that various modifications can be made without departing from the spirit of the invention. Accordingly, the invention is limited only by the following claims.

The invention claimed is:

1. An internal combustion engine including at least one cylinder with longitudinally-separated exhaust and intake ports, and a pair of pistons disposed in opposition to one another in a bore of the cylinder, in which a combustion chamber having an elongated ellipsoidal shape is defined between opposing end surfaces of the pistons, and the end surface of at least one of the pistons has a circumferential area defining a periphery of the end surface and a bowl within the periphery, the bowl defining a concave surface with a first portion curving inwardly from a plane containing the circumferential area toward the interior of the piston and a second portion curving outwardly from the interior of the piston through the plane containing the circumferential area.

2. The internal combustion engine of claim **1**, in which the opposing pistons are oriented in the bore such that the elongated ellipsoidal shape is defined between the bowls when the pistons are near respective top dead center (TDC) positions in the bore.

3. The internal combustion engine of claim **2**, in which at least one injector port is provided in the cylinder at a position on a major axis of the combustion chamber.

4. The internal combustion engine of claim **1**, in which each end surface further includes a convex surface within the periphery and curving outwardly from the plane containing the circumferential area, and the convex surface meets the second portion of the concave surface to form a ridge.

5. The internal combustion engine of claim **4**, in which the opposing pistons are oriented in the bore such that the convex surface of each piston end surface defines a squish zone with the second portion of the concave surface of the other piston when the pistons are near respective top dead center (TDC) positions in the bore.

6. The internal combustion engine of claim **5**, in which opposing concave and convex surface portions in each squish zone cause squish flow toward a cavity defined between the bowls when the pistons are near respective TDC positions in the bore.

7. The internal combustion engine of claim **6**, in which at least one injector port is provided in the cylinder at a position on a major axis of the cavity.

8. A method for operating an internal combustion engine including at least one cylinder with longitudinally-separated exhaust and intake ports, and a pair of pistons disposed in opposition to one another in a bore of the cylinder, by admitting a charge of air into the bore through the intake port as the pistons move from respective bottom dead center positions in the bore, causing a tumbling motion in the charge of air between opposing end surfaces of the pistons as the pistons move toward respective top dead center positions in the bore, and injecting a charge of fuel into an elongated ellipsoidal combustion chamber defined between opposing bowls on end surfaces of the pistons as the pistons near top dead center.

9. The method of claim **8**, in which injecting a charge of fuel into the charge of air includes injecting the fuel along a major axis of the combustion chamber.

10. The method of claim **8**, in which a swirling motion is imposed on the charge of air admitted into the bore.

11. The method of claim **10**, the combustion chamber having an elongated ellipsoidal shape with a major axis.

12. The method of claim **11**, in which injecting a charge of fuel into the charge of air includes injecting the fuel along the major axis.

13. A method for operating an opposed piston engine including at least one cylinder with longitudinally-separated exhaust and intake ports, and a pair of pistons disposed in opposition for reciprocating in a bore of the cylinder, by forming a combustion chamber having an elongated ellipsoidal shape between the end surfaces of the pistons as the pistons move toward respective top dead center positions in the bore, providing squish flows of charge air into the combustion chamber in directions that are skewed with respect to a major axis of the elongated ellipsoidal shape, generating at least one tumbling motion of charge air in the combustion chamber in response to the squish flows and swirling charge air, and injecting fuel into the combustion chamber.

14. The method of claim **13**, in which injecting a charge of fuel into the combustion chamber includes injecting the fuel along the major axis.

15. The method of claim **13**, in which generating at least one tumbling motion includes generating a first tumbling motion about a major axis and generating a second tumbling motion about an axis orthogonal to the major axis.

16. The method of claim **13**, in which injecting a charge of fuel into the combustion chamber includes injecting opposing sprays of fuel along the major axis.

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